NASA TECHNICAL MEMORANDUM

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PAGEOS PROJECT

COMPILATION OF INFORMATION FOR USE OF EXPERIMENTER

by David E. Bowker

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1967

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PREFACE

This publication is intended to provide the experimenter with information essential to participation in the PAGEOS data collection and analysis program. A general description of the satellite triangulation method and the camera requirements for passive satellite photography is given. The PAGEOS project is a part of the National Geodetic-Satellites Program which is under the direction of the National Aeronautics and Space Administration.

CONTENTS

ABBREVIATIONS AND SYMBOLS

Abbreviations

ACIC	Aeronautical Chart and Information Center
ACSM	American Congress on Surveying and Mapping
AFB	Air Force Base
AFCRL	Air Force Cambridge Research Laboratories
AGU	American Geophysical Union
AIAA	American Institute of Aeronautics and Astronautics
AMS	Army Map Service
ANNA	Acronym for Army, Navy, NASA, Air Force Satellite
ASP	American Society of Photogrammetry
BC-4	camera designation
BRL/APG	Ballistic Research Laboratories/Aberdeen Proving Ground
C&GS	Environmental Science Services Administration/Coast and Geodetic Survey
DOC	Department of Commerce
DOD	Department of Defense
DSD	Data System Division
ESSA	Environmental Science Services Administration
GEOS	Acronym for Geodetic Earth Orbiting Satellite
GIMRADA	Geodesy, Intelligence and Mapping Research and Development Agency

GOCC	Geodetic Operations Control Center
GSDS	Geodetic Satellites Data Service
GSFC	Goddard Space Flight Center
GST	Greenwich sidereal time
K-50	camera designation
LRC	Langley Research Center
MOTS	Minitrack Optical Tracking Station
NASA	National Aeronautics and Space Administration
NGSP	National Geodetic Satellites Program
NWL	Naval Weapons Laboratory
OCE	Office of Chief of Engineers
OSU	Ohio State University
PAGEOS	Acronym for Passive Geodetic Earth Orbiting Satellite
PC-1000	camera designation
QC	Quality control
R&RR	Range and Range Rate
SAO	Smithsonian Astrophysical Observatory
SECOR	Sequential Collation of Range
SSDC	Space Science Data Center
UC	University of California

USAF	United States Air Force
UT	Universal time
VLF	Very Low Frequency (Radio Wave Propagation for Timing Purposes)

Symbols

a	semimajor axis of Keplerian orbit
e	eccentricity of Keplerian orbit
f	true anomaly of Keplerian orbit
f/	camera lens stop number
$F(\psi)$	phase factor
i	inclination of Keplerian orbit
r	radius of satellite; also distance to satellite (orbital radius vector)
R	range of satellite; also reflectivity of satellite
U,V,W	earth-fixed geodetic coordinates referred to polar axis and Greenwich meridian
X,Y,Z	inertial coordinates referred to polar axis and vernal equinox
β	latitude (geocentric)
λ	longitude, counterclockwise from Greenwich meridian
γ	vernal equinox
ϕ	phase angle correction
ψ	phase angle
ω	argument of perigee, from node of Keplerian orbit
Ω	longitude, from vernal equinox, of node of Keplerian orbit (right ascension)

A. INTRODUCTION

National Geodetic Satellites Program (NGSP)

The National Aeronautics and Space Administration (NASA) is responsible for conducting a National Geodetic Satellites Program that will satisfy the geodetic satellite requirements of the scientific community. The primary objective of the program is to secure global geodetic satellite measurements which will appreciably improve the accuracy of the size and shape of the earth and its gravity field. Secondary objectives are the location of isolated islands and the evaluation of new high-precision satellite mensuration techniques.

NASA has authorized eight principal investigators to collect and/or analyze data for the NGSP. In addition, NASA directly sponsors four principal investigators. The contributions of the PAGEOS program to their efforts can best be realized by reviewing the basic objectives of the NGSP and the individual requirements of the principal investigators authorized to receive data from the Geodetic Satellites Data Service (GSDS). The program objectives are as follows:

(a) Connect geodetic data to establish one world datum and adjust all local data to the common earth center of mass so that positions of geodetic control stations will have a relative accuracy of ± 10 meters or better in an earth center-of-mass coordinate system.

(b) Define the structure of the earth's gravitational field (to five parts in 10^8) and refine the location and magnitude of significant gravity anomalies.

(c) Improve positional accuracy of satellite tracking sites.

(d) Compare the accuracy of existing high-precision satellite-measuring techniques and formulate new high-accuracy processing methods and system calibration procedures.

Each NASA-sponsored investigator and the C&GS investigator is responsible for the publication of the results of the individual's investigations. In addition, the NASA-sponsored principal investigators are required to cooperate in the compilation of the investigation results to produce a handbook which will synthesize the results of the NGSP. This handbook will include a mathematical analysis of the gravitational field of the earth as seen from satellite altitudes; a map of the earth interrelating various geodetic datums and placing these datums and isolated points on a standard earth-centered coordinate system; and a discussion of various observing techniques with an intercomparison of their effectiveness and accuracy.

The wide range of scientific investigations leading to the program objectives are essentially of three basic types: geometric, gravimetric, and geodetic tracking systems intercomparison. These investigations will utilize established geodetic techniques which incorporate the data from one or more of the geodetic observational systems within the NGSP. PAGEOS will yield optical camera data essential to the geometric analysis. GEOS-A provides range, range and range rate, Doppler, and optical camera and laser data. Applications of the data are discussed in the investigation plans given below.

Another basic objective of the National Geodetic Satellites Program is to encourage international participation in ground-based observations, data acquisition, and data analysis. In this respect, the low initial cost of observation equipment, as well as the number of foreign facilities already operational, make the PAGEOS program particularly attractive. This manual will furnish the potential experimenter with the information required for participation in the observation program.

Investigation Plans

The eight principal investigators for the NGSP are:

LAWRENCE W. SWANSON
Project Manager, Geodetic Satellite Project
Environmental Science Services Administration
DOC – Coast and Geodetic Survey
Washington Science Center
Rockville, Maryland

JOHN S. McCALL
Chief, Geodesy Branch
Mapping and Geodesy Division
Office of Chief of Engineers
Department of the Army
Washington, D.C.

MARCUS ROSENBAUM
AFNINC
Headquarters USAF
Pentagon
Washington, D.C.

CHARLES A. LUNDQUIST
Assistant Director
Smithsonian Astrophysical Observatory
Cambridge, Massachusetts

IVAN I. MUELLER
Associate Professor
Department of Geodetic Science
Ohio State University
Columbus, Ohio

WILLIAM M. KAULA
Professor of Geophysics
Institute of Geophysics and Planetary Physics
University of California
Los Angeles, California

RICHARD ANDERLE
Head Astronautics Division
Computations and Analysis Laboratory
Naval Weapons Laboratory
Dahlgren, Virginia

JOHN H. BERBERT
Head, Operation Evaluation Branch
NASA Goddard Space Flight Center
Greenbelt, Maryland

The nature of the investigations does not permit any single investigator exclusive use of a set of data. The specific responsibilities of investigators, stated in the subsequent paragraphs of this section, indicate the degree of data exchange within the NGSP. Additional information on the investigation plans can be found in references 1 and 2.

Responsibilities of investigators.- Lawrence W. Swanson, C&GS, is responsible for the establishment of a worldwide geometric network, independent of gravity, to an accuracy approaching one part in 500,000, which will connect the major datums now in existence to the maximum possible extent. Internally generated optical data only will be required.

John S. McCall, OCE, will observe the passive geodetic satellites in conjunction with the Coast and Geodetic Survey, a component of the Environmental Science Services Administration/Department of Commerce, efforts in establishing a world geometric network, and will perform radio ranging observations on the GEOS satellite to accomplish intercontinental, interdatum, and interisland geodetic ties. Selected SECOR and R&RR final data, GSFC and USAF laser data, and various optical final data will be required.

Marcus Rosenbaum, AFNINC, will connect the major geodetic datums into a unified system and adjust all local datums to the common center of mass of the earth, will define the structure of the earth's gravitational field, and will improve positional accuracies of satellite observation sites and calibrate measuring equipment. Various optical final data and selected SECOR and R&RR final data will be required.

Charles A. Lundquist, SAO, plans to obtain a better representation of the earth's gravitational potential, improve the knowledge of the geodetic positon of SAO observing stations, improve the orientations of various geodetic datums, and compare the geodetic results derivable from optical data with those from electronic data. Doppler, R&RR, SECOR, optical camera and laser data, as well as the internally generated Baker-Nunn data will be required.

Ivan I. Mueller, OSU, will obtain a unified world geodetic datum and convert the coordinates of other points situated on the national datum to the world datum. Selected SECOR and R&RR final data, various optical camera final data, and laser data are required.

William M. Kaula, UC, will determine variations of the gravitational field of the earth. Optical, Doppler, R&RR, and SECOR tracking data are required.

Richard Anderle, NWL, will define the structure of the earth's gravitational field to 5 parts in 10^8, refine the location and magnitude of large gravity anomalies, and improve the positional accuracy of the TRANET tracking sites and calibrate the Doppler tracking equipment. Internally generated Doppler data only will be required.

John H. Berbert, GSFC, plans to improve the present knowledge of the accuracies of the radio and optical satellite geodetic tracking systems, and produce newer, more accurate data processing procedures. All types of final data, selected original data, and selected semiprocessed data will be needed.

PAGEOS.- The Passive Geodetic Earth Orbiting Satellite (PAGEOS), an Echo I type inflatable sphere, is a response to the need for worldwide geodetic data acquisition, primarily for refining the worldwide geodetic network and the relationship of intercontinental, interisland, and interdatum geodetic ties. A necessary phase of this effort will be the establishment of a multistation geometric network essentially free of any gravity hypothesis. The geometric location of each station will be determined within a single reference system by simultaneous photography of PAGEOS against a star background with two or more ground-based cameras.

Although several principal investigators will utilize PAGEOS data and different camera teams are planned to observe the passive satellite, the C&GS has the primary responsibility of collecting and reducing BC-4 camera observations of PAGEOS in cooperation with the Army Map Service (AMS). The C&GS has a high priority for geodetic control throughout the United States and possessions and, to a lesser extent, for worldwide geodetic control.

The Smithsonian Astrophysical Observatory, under NASA sponsorship, will be responsible for obtaining PAGEOS observations with the Baker-Nunn cameras and for analyzing other observational data obtained by the C&GS and international observers. Ivan I. Mueller, also under NASA sponsorship, is responsible for analysis of PAGEOS and other satellite data to define a unified world geodetic system for the NGSP.

Application of Echo I to Satellite Triangulation

Originally intended for passive communication experiments, the Echo I satellite has been used extensively in this country and abroad to evaluate the technical feasibility of satellite triangulation. Investigators have experienced various degrees of success; the best reported accuracy meets the requirements for first-order triangulation.

The C&GS has established horizontal coordinates about 1500 kilometers (809 n. mi.) apart in the eastern United States. (See ref. 3.) This effort marked the beginning of observations within a North American continental network which will eventually serve to densify the worldwide PAGEOS network.

French geodesists have made preliminary ties between France and North Africa with synchronous photographs taken of Echo I. (See ref. 4.) The Soviet Union has extended a network more than 10 000 kilometers (5399.6 n. mi.) across Russia, confined mainly to the southern latitudes because of the $47\frac{1}{2}^{\circ}$ inclination of the Echo I orbit. (See ref. 5.)

SAO has also used Echo I, along with numerous other satellites, to establish a geometric network with the Baker-Nunn stations.

Requirements for PAGEOS

PAGEOS is an inflatable, aluminized Mylar balloon of the Echo I type. Its optical properties and orbit are consistent with requirements for conducting global geodetic measurements such that an intermediate size triangulation network of control points can be established. In particular, the original 36-station network proposed by the Coast and Geodetic Survey (see section D) was used to establish necessary control for the orbit selection.

A number of conditions were imposed on the orbit to satisfy the requirements of this network. These conditions were:

(1) The initial apogee must be in the range of 4000 to 4500 kilometers (2159.8 to 2294.8 n. mi.).

(2) The inclination must be in the range 80° to 90°.

(3) The orbit must have at least a 5-year lifetime.

(4) The orbit must permit a large number of suitable two-station and three-station simultaneous observations.

Altitude and inclination requirements are related to the network geometry and location. In the interest of geometric strength in the analysis, the satellite range should be roughly equivalent to the base-line distance between adjacent stations, which averages about 4100 kilometers (2213.8 n. mi.) in the original C&GS 36-station network. Although an inclination of 90° at first appeared imminent, an orbit stability and station observation study indicated that a prograde inclination of 87° was a better choice.

A 5-year lifetime is a conservative estimate of the time required to complete the observations. Twelve BC-4 camera teams will be deployed by the C&GS and the AMS on a logistics basis during the BC-4 data collection program. NASA (MOTS) and NASA-sponsored (SAO) teams will also observe PAGEOS throughout its lifetime. In addition, a large international participation is expected (see appendixes I, II, and III).

PAGEOS was successfully launched from the Western Test Range on June 23, 1966. The initial orbital elements were as follows:

Epoch: June 24, 1966 – 01 hr 34.00 min UT

Semimajor axis, km (n. mi.)	10614.79 (5731.5)
Eccentricity	0.00248
Inclination, deg	86.974
Mean anomaly, deg	108.411
Argument of perigee, deg	248.328
Motion minus, deg/day	0.8239
Right ascension of ascending node, deg	337.125
Motion minus, deg/day	0.0887
Anomalistic period, min	181.38952

B. DISCUSSION OF SATELLITE TRIANGULATION

General Discussion

Spatial triangulation can be employed to establish geometrical triangulation of a selected number of nonintervisible sites on the physical surface of the earth. Artificial satellites which are sufficiently illuminated to be simultaneously photographed from two or more widely separated sites are well suited for this purpose. Because of its orbital motion the satellite must be photographed against a star background to yield direction measurements.

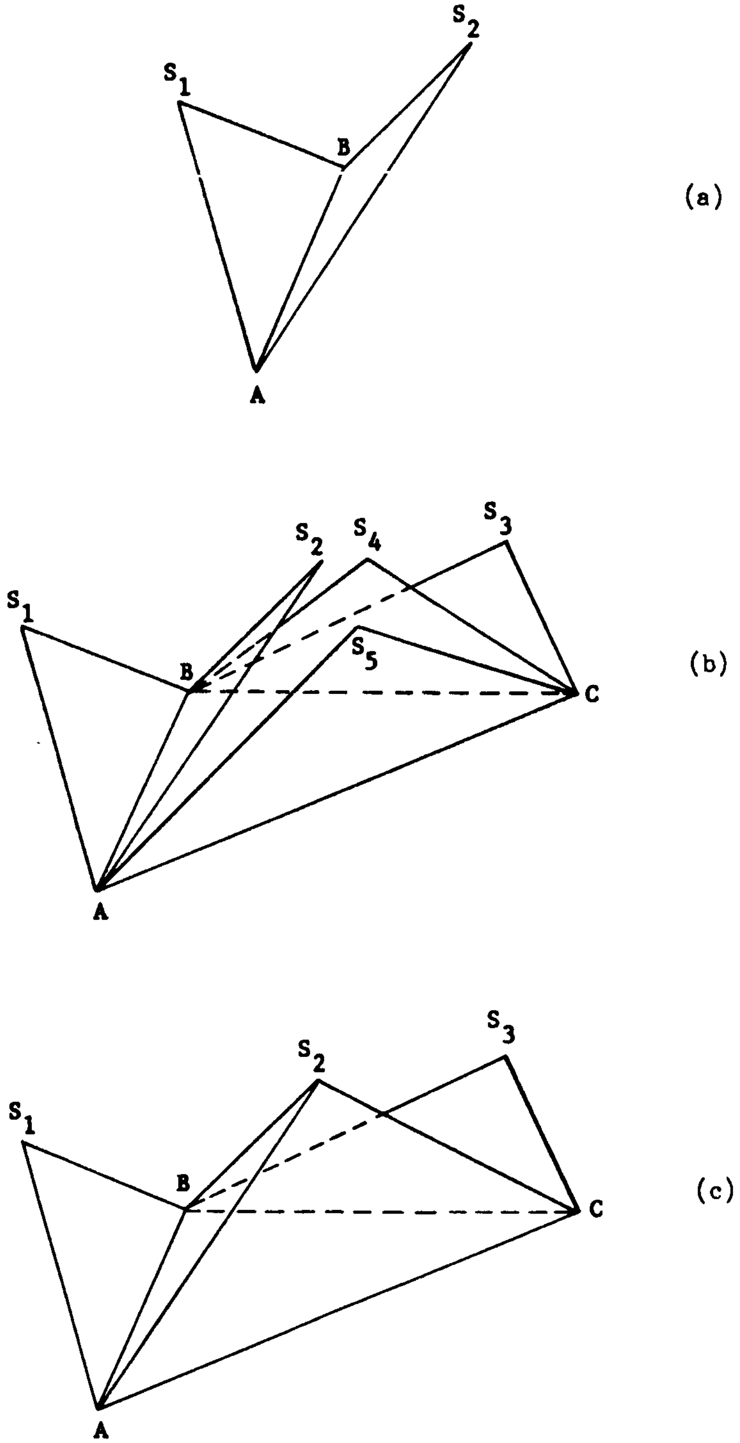
The reference system into which the satellite direction can be interpolated is the right-ascension declination system, which has one axis coincident with the earth's rotational axis. Since the stars are essentially at infinity, their direction coordinates are insensitive to translation and cannot be used for scale determination. Thus, the length of one of the base lines in the triangulation network must be established by conventional methods.

The basic principle underlying satellite triangulation is that two conjugate rays emanating from the endpoints of a base line AB (fig. B-1a) define a plane in space whose spatial coordinates can be computed from the measured direction cosines of the two rays. (See fig. B-2.) Two additional conjugate rays define a second plane, and the intersection of the two planes defines the orientation of the base line AB. A spatially oriented triangle ABC is formed when two base lines with a common endpoint are intersected with a plane that contains neither of the two lines and whose orientation is known.

It is apparent that five planes are necessary and sufficient for establishing a unique solution for a spatially oriented triangle (fig. B-1b). This statement means that 5 satellite positions and 10 photographs are required. If it is possible for three stations to photograph the satellite simultaneously, then only three satellite positions and seven photographs are required (fig. B-1c). The minimum number of observations required for a unique solution will establish the accuracy, but a redundancy in data collection is necessary to establish confidence and identify systematic errors.

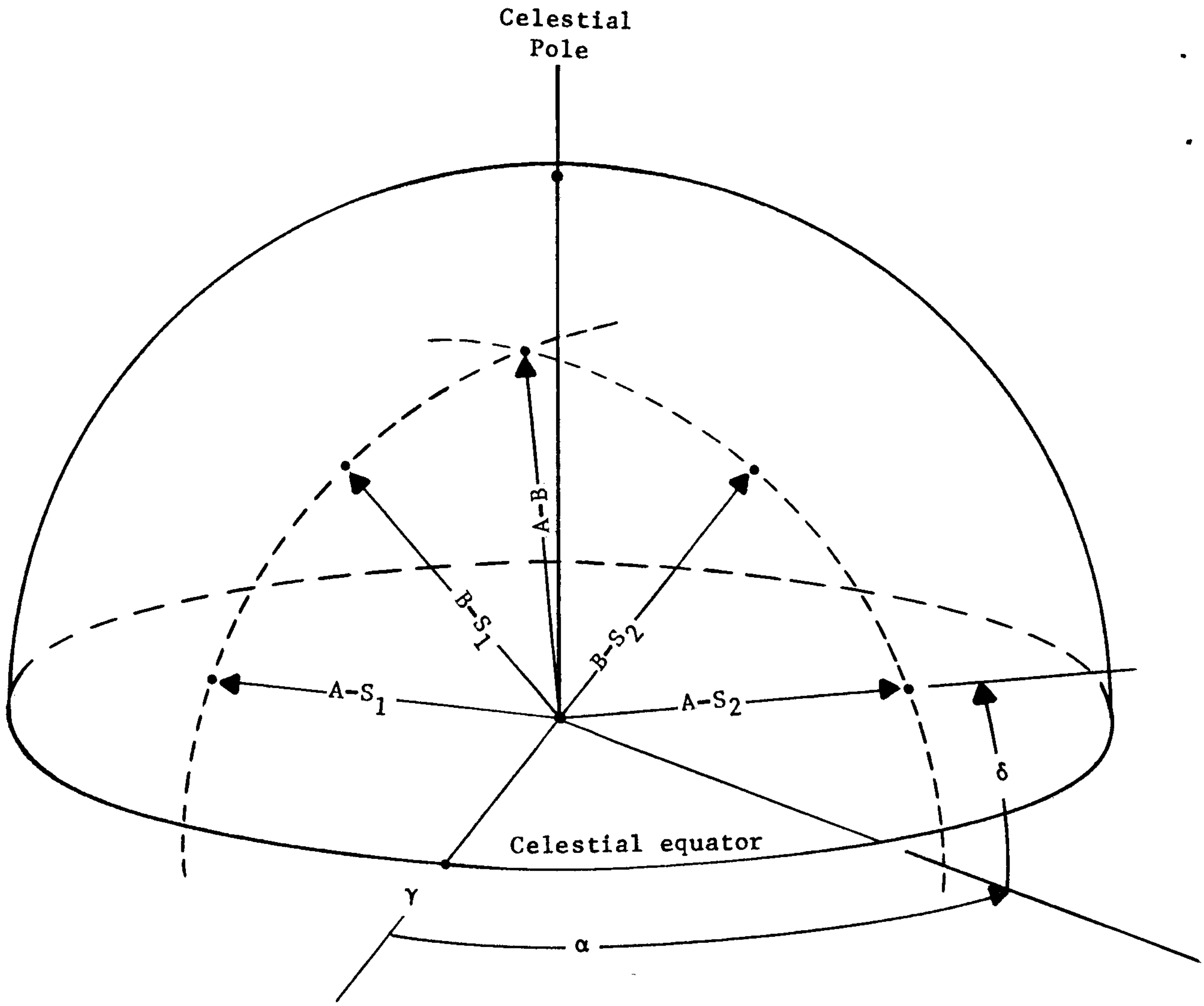
Geometry and Observation Considerations

Several conditions are usually imposed on the satellite observations to strengthen the geometric solution to the spatially oriented triangle. The best solution for the direction cosines of a base line is obtained when the two planes containing the base line are perpendicular. Since this condition is not always possible, it is considered sufficient to limit the angle of intersection to 60° or greater. Furthermore, to avoid scale degradation, the satellite range should be roughly equal to the length of the base lines. This



A, B, C - camera sites
S_1, ---, S_5 - satellite positions

Figure B-1.- Procedure for establishing stellar orientation of ground-based triangle.



α	Right ascension
δ	Declination
$A-S_1$, $B-S_1$	Direction of satellite when viewed from stations A & B, respectively, at time T_1
$A-S_2$, $B-S_2$	Direction of satellite when viewed from stations A & B, respectively, at time T_2, corrected to time T_1
A-B	Direction of base line A-B at time T_1 - point of intersection of two planes passing through $A-S_1$, $B-S_1$ and $A-S_2$, $B-S_2$, respectively

Figure B-2.- Determination of stellar orientation of base line.

limitation implies a high degree of symmetry in the ground-based triangles and the satellite range.

To limit the magnitude of the refraction anomaly and to assure a sufficient number of stars for data reduction, the station-satellite line should have a minimum elevation of about 30°.

Synchronization can be achieved by placing the timing mechanism in the satellite (such as in the flashing-light ANNA 1B and GEOS) or by instrumenting the tracking camera with accurately timed shutters (such as the cameras used to photograph the Echo and PAGEOS satellites (see sec. F)). The United States Air Force (USAF) and NASA-Goddard Space Flight Center (NASA-GSFC) consider the advantage of an active satellite to compensate for the low number of flashes available per observation. (See ref. 6.) The advantage is a relatively inexpensive mobile camera without any timing equipment. The Coast and Geodetic Survey and the Smithsonian Astrophysical Observatory equip their cameras with chopping shutters (ref. 7), and thus many images of an Echo-type satellite per photograph are obtained.

The NASA-GSFC and SAO cameras, which were not specifically designed for satellite triangulation, use sidereal tracking to improve the number and quality of stellar images, whereas the C&GS and USAF cameras are fixed to eliminate tracking jitter.

C. SATELLITE CHARACTERISTICS

Fabrication

PAGEOS is constructed from 0.5 mil (0.00127 cm) thick plastic film (poly(ethylene terephthalate)) with a vapor-deposited aluminum coating (approx. 2200 Å) on the outside surface. The aluminum coating presents a highly reflective surface to the incident sunlight and also protects the plastic film from damaging ultraviolet radiation.

Eighty-four (84) gores, 45 inches (114 cm) wide at the center and 157 feet (47.85 m) long, were tailored for fabrication of the satellite (fig. C-1a). They were butted together and sealed with a 1.0-inch-wide (2.54-cm) tape made from the same material as that used for the gores (fig. C-1b). A thin layer of thermosetting resin applied to the plastic side of the tape served as the adhesive. The polar ends terminated in a dual polar cap configuration (fig. C-1c). The inner cap was 1.0-mil-thick (0.00254-cm) plastic film, 38 inches (96.52 cm) in diameter with a 2.0-inch (5.08-cm) bonding area at the periphery, and was primarily intended to strengthen the polar regions. The outer cap was made from gore material and was 40 inches (101.6 cm) in diameter with ten (10) reinforced 0.0625-inch (0.1587-cm) vent holes. The edge of this cap was painted with a conducting paint and sealed over with a 1.0-inch-wide (2.54-cm) tape. In addition, a 0.25-inch-wide (0.63-cm) strip of 1.0-mil aluminum foil was imbedded nearby in a conducting paint and sealed over with a 1.0-inch-wide (2.54-cm) tape. The conducting rings assure the electrical continuity of all the gores; the gores otherwise may be electrically discontinuous at the gore seams.

Before the last gore was sealed, the sphere was "pleat" folded along longitudinal lines (fig. C-2a). One hundred and sixty-eight (168) reinforced 0.0625-inch (0.15-cm) vent holes, evenly spaced along a meridian which circumscribes the sphere, were positioned on the outer sides of the folded sphere. A uniform mixture of 10 pounds (4.54 kg) of benzoic acid and 5 pounds (2.27 kg) of anthraquinone (the subliming inflation compounds) was evenly distributed between the folds within 26.2 feet (7.99 m) of the equator. Fifteen pounds (6.80 kg) of anthraquinone was distributed uniformly throughout the remainder of the sphere. The last gore was then sealed and the sphere was folded in a rotated "accordion" pattern as it was packaged into the canister (fig. C-2b).

The structural quality of the sphere was partially demonstrated by a series of ground-based tests conducted with a full-scale static-inflated prototype (fig. C-3). A deployment test was also conducted inside a 60-foot-diameter (18.29-m) vacuum sphere.

Observations of PAGEOS in orbit with radar, photometer, and photographic techniques indicate that the satellite has been successfully deployed and is suitable for geometric satellite triangulation measurements.

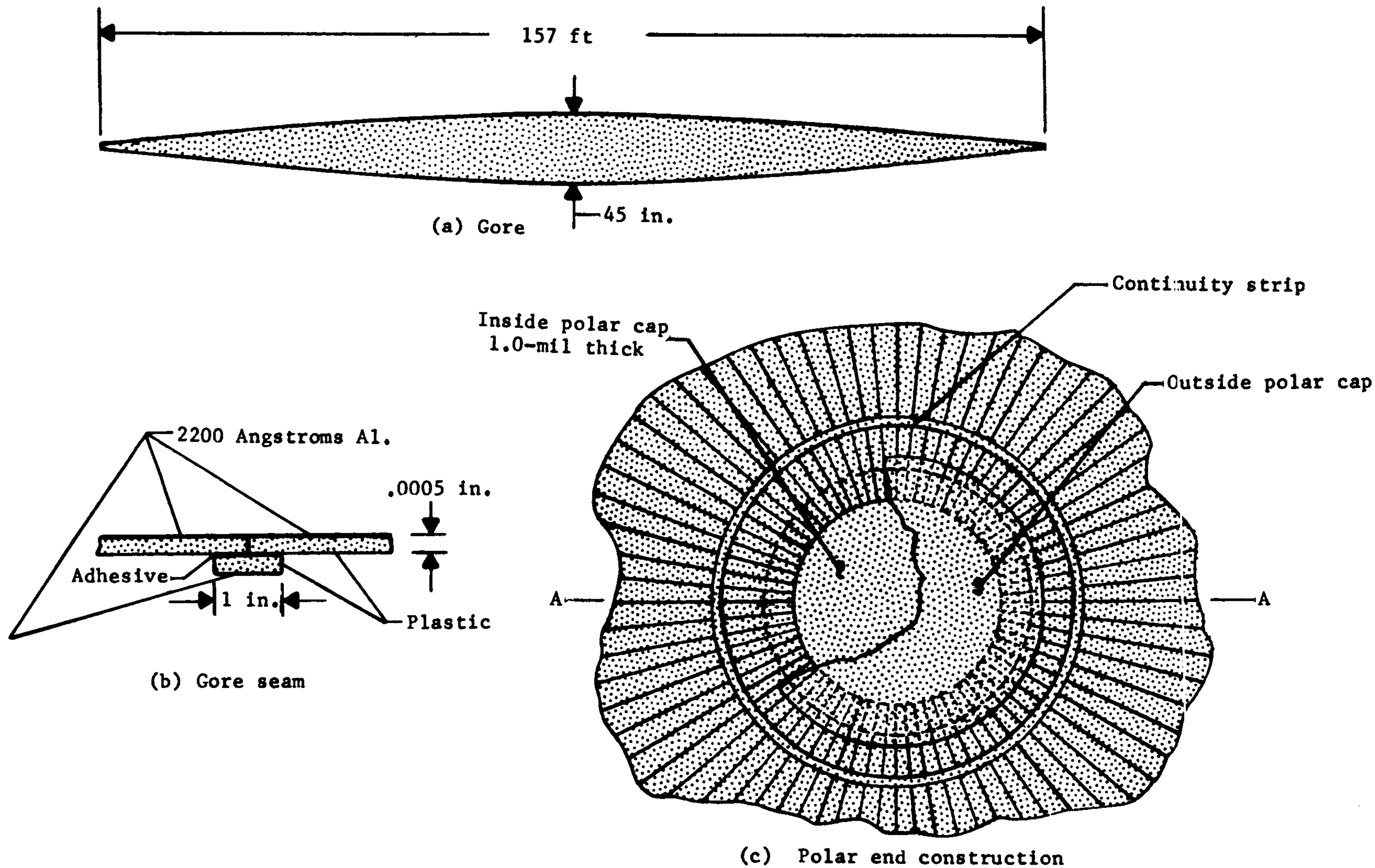


Figure C-1.- Fabrication of 100-foot-diameter (30.48 m) inflatable sphere.

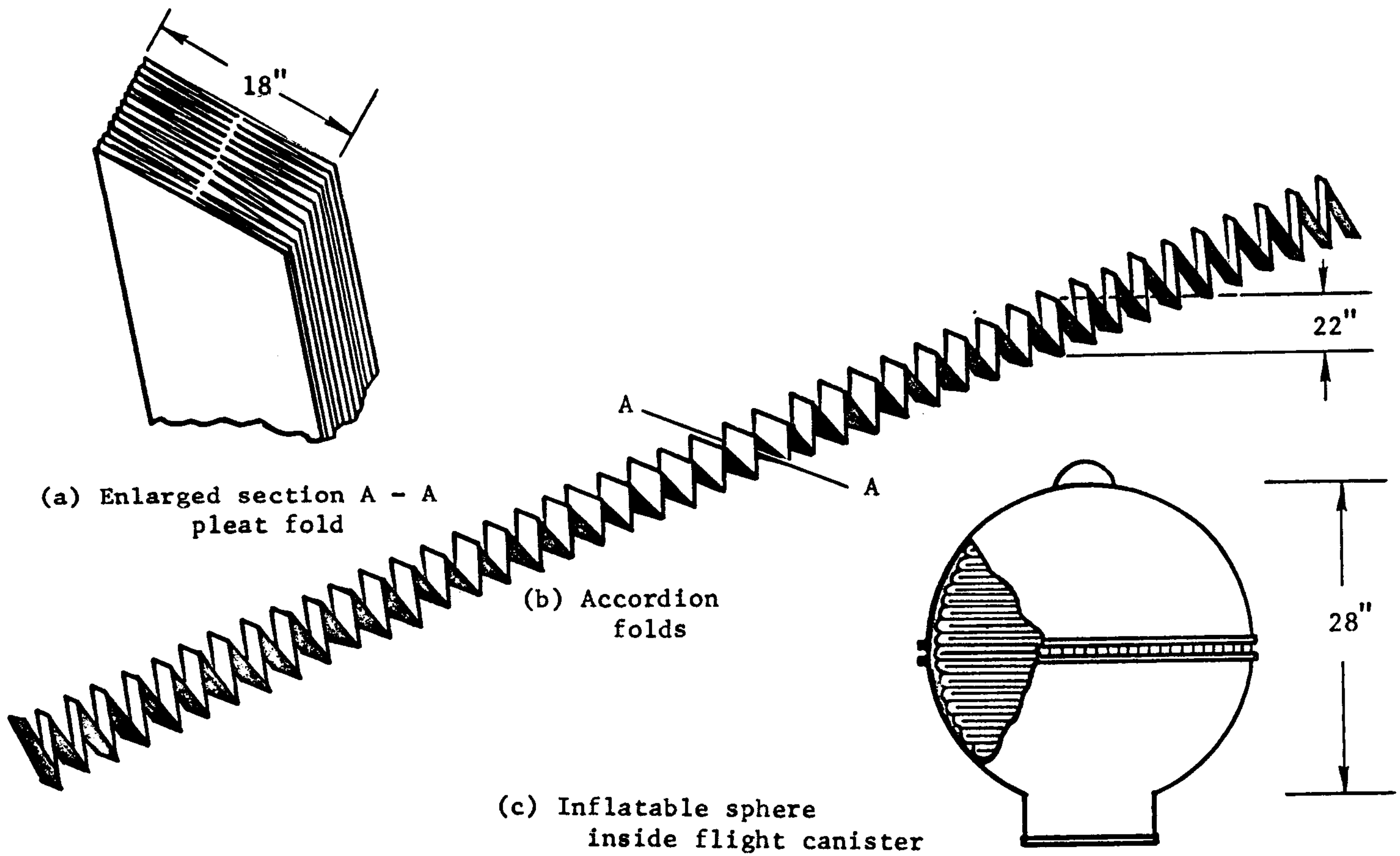


Figure C-2.- Folding and packaging of PAGEOS for launch.

Weight

The components were weighed individually before the sphere was fabricated, and then the packaged canister assembly was weighed as a final check. The total weights are as follows:

Inflatable sphere	119.234 lbm ± 0.01 lbm	(54.0845 kg ± 0.0045 kg)
Benzoic acid	10.156 lbm ± 0.01 lbm	(4.6068 kg ± 0.0045 kg)
Anthraquinone	20.391 lbm ± 0.01 lbm	(9.2494 kg ± 0.0045 kg)
Canister assembly	38.99 lbm ± 0.01 lbm	(17.6859 kg ± 0.0045 kg)

The canister pressure was reduced to 0.8 to 1.0 torr (1 torr = 133.3 N/m^2 ≈ 1 mm Hg) after assembly. This pressure was limited by the vapor pressure of benzoic acid (≈0.15 torr at 21° C).

Reflectivity

The reflectivity R of the aluminum coating on PAGEOS is as follows:

$R_{specular}$	0.862 ± 0.0046
$R_{diffuse}$	0.029 ± 0.0046
R_{total}	0.891 ± 0.0032

These values are weighted to represent the solar spectrum within the range 3,600 Å to 7,000 Å.

Sphericity

During the static inflation test of a full-scale prototype sphere (fig. C-3), the diameter was monitored at eight positions on the sphere's equator and along the polar axis. At a skin stress of 700 pounds per square inch (48.265×10^5 N/m^2), the predicted initial stress when fully inflated in orbit, the diameter was as follows:

Average diameter	99.98 ft	(30.47 m)
Maximum diameter	100.19 ft	(30.54 m)
Minimum diameter	99.61 ft	(30.36 m)

NASA-Langley Research Center will conduct a photometric analysis of the satellite in orbit for several weeks, similar to a study made of Echo I.

Time and Position Dependent Properties in Orbit

Mass as a function of time after deployment.- The time dependent mass loss of the satellite (ref. 8) is due to leakage of the inflation gases through the small holes located

Figure C-3.- Fully inflated 100-foot-diameter (30.48 m) PAGEOS.

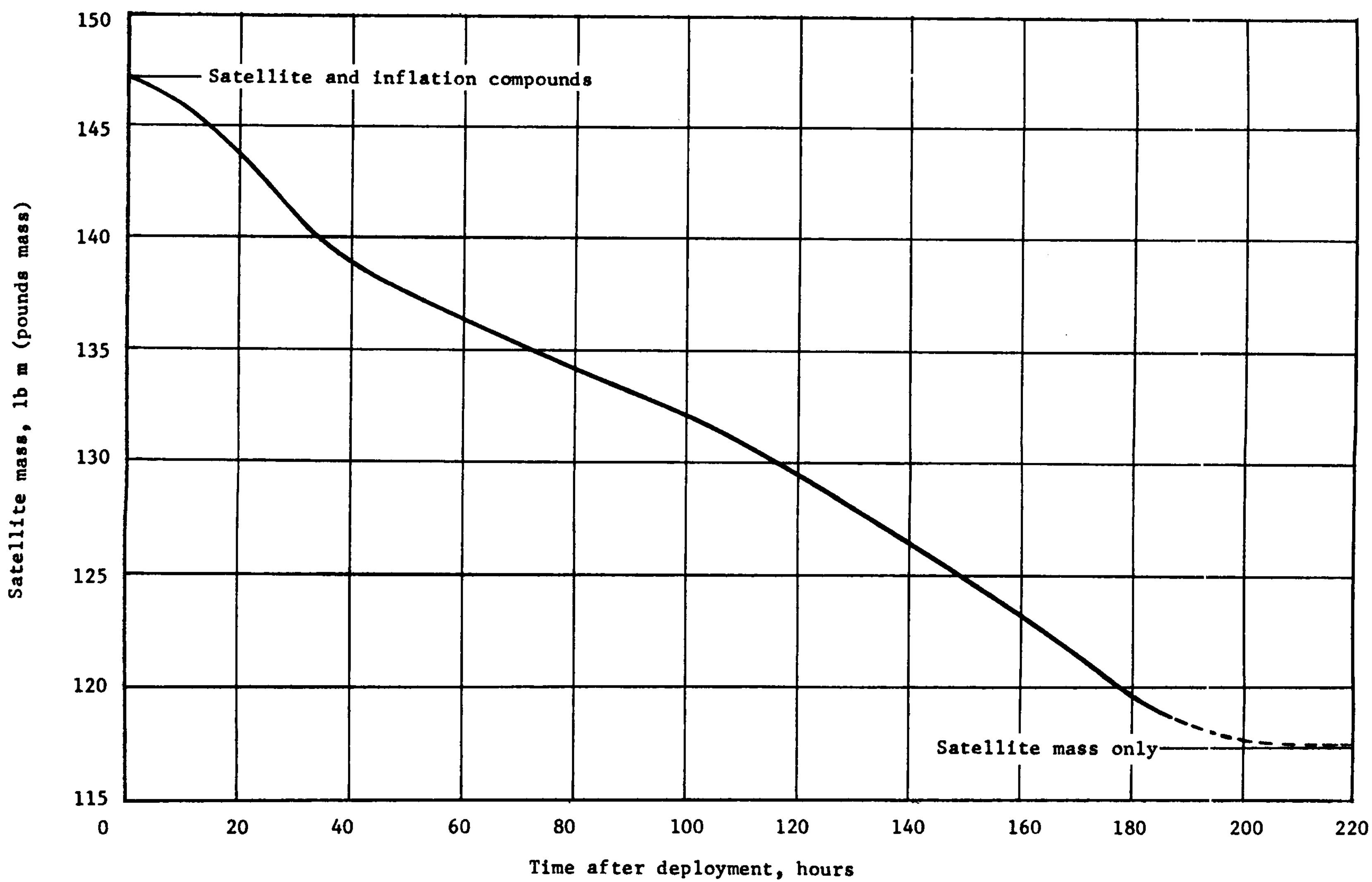


Figure C-4.- Satellite mass as a function of time after deployment.

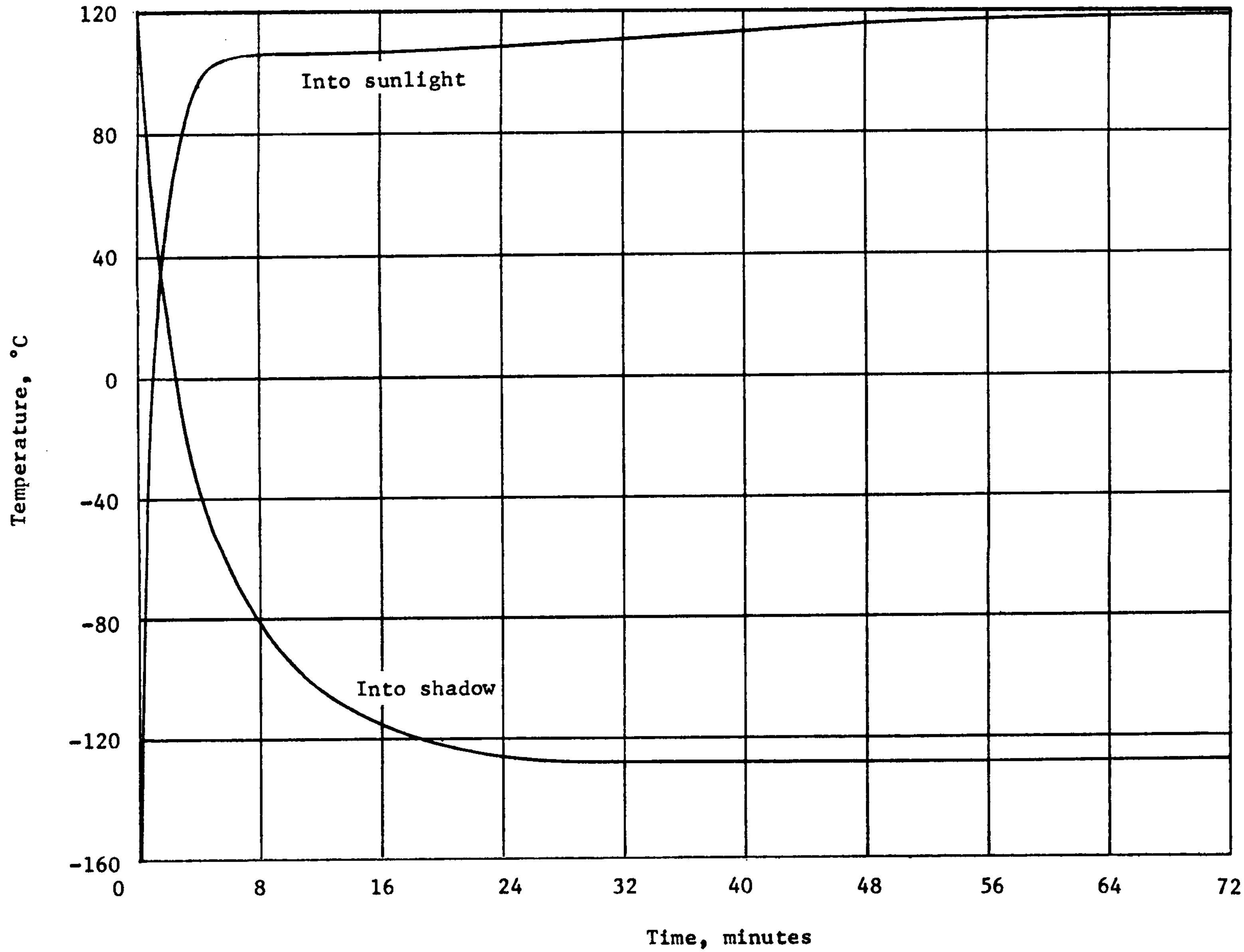


Figure C-5.- Dynamic thermal response of the passive geodetic satellite in its passage from sunlight to shadow and shadow to sunlight.

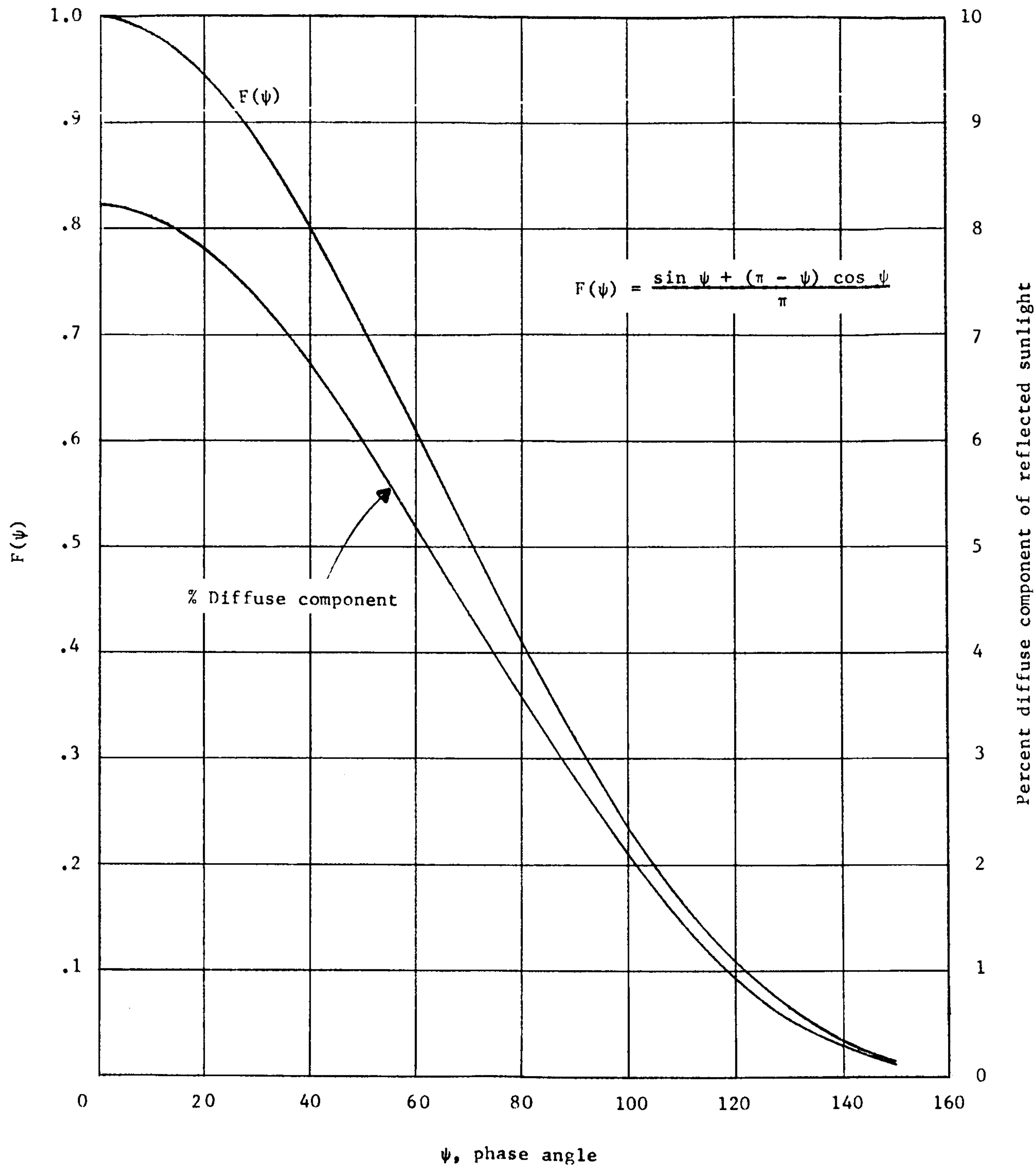


Figure C-6.- Diffuse reflected sunlight from PAGEOS as a function of the phase angle.

along the sphere's meridian plus those caused by micrometeoroid puncture. Figure C-4 gives the predicted variation of mass with time of PAGEOS for the first 186 hours after deployment (must be corrected for actual weight). The temperature was assumed to be 119° C and the micrometeoroid hole area formation rate was taken as 3.25×10^{-4} cm^2/sec (0.504 in^2/sec), which is presently believed to be an upper limit.

Temperature as a function of time.- Figure C-5 gives the dynamic thermal response of PAGEOS (ref. 8) upon entering and leaving the earth's shadow. The earth-sun line is assumed to be in the plane of the circular orbit. When passing into the earth's shadow an equilibrium temperature of -132° C is reached in about 36 minutes. The time necessary for the satellite to attain its original shadow entrance temperature upon entering sunlight is approximately 8 minutes. The gradual increase in temperature from 107° C to 119° C is due to the increase in earth-reflected thermal energy as the satellite moves toward the sun. An abrupt boundary between the sunlight and shadow zones was assumed in this analysis (that is, no penumbra was considered).

Specular and diffuse component of reflected sunlight.- The reflected sunlight from the satellite's surface is a function of the camera-satellite-sun angle (ref. 9), or phase angle ψ. For a 0° phase angle the diffuse component accounts for about 8 percent of light reflected toward the observer. As the phase angle increases, the diffuse component will diminish according to the formula given in figure C-6. The phase factor $F(\psi)$ is unity for $\psi = 0^{\circ}$, $1/\pi$ for $\psi = 90^{\circ}$, and 0 for $\psi = 180^{\circ}$. With a 30° camera elevation angle and the sun 18° below the horizon, the phase angle may vary from 12° minimum to 132° maximum, and result in a variation of the diffuse component from 8 percent to 0.5 percent of the total reflected light.

Phase angle correction.- The position of the sun's image on the highly specular surface of the satellite will only coincide with the center of the sphere, as viewed by an observer, when the phase angle is zero. For tracking and geodetic purposes, it is therefore necessary to adjust all direction measurements to a common origin such that the data will be geometrically consistent. The phase angle correction given in figure C-7 will refer the direction measurement to the center of the satellite. The diffuse component of illumination of PAGEOS is not significant in this application.

Stellar magnitude.- The stellar magnitude of PAGEOS is given as a function of the slant range in figure C-8. When the range is 4250 kilometers (2294.8 n. mi.) and the phase angle is 90°, the magnitude is about +2.3. If the apogee of the PAGEOS orbit should reach 7500 kilometers (4049.7 n. mi.) (for an eccentricity of about 0.3), the maximum slant range for a 30° camera elevation will be less than 10,000 kilometers (5399.6 n. mi.), and thus PAGEOS will have a magnitude of about +4, which is still satisfactory for satellite triangulation.[1]

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[1]Private communication with Hellmut H. Schmid and Eugene A. Taylor of C&GS.

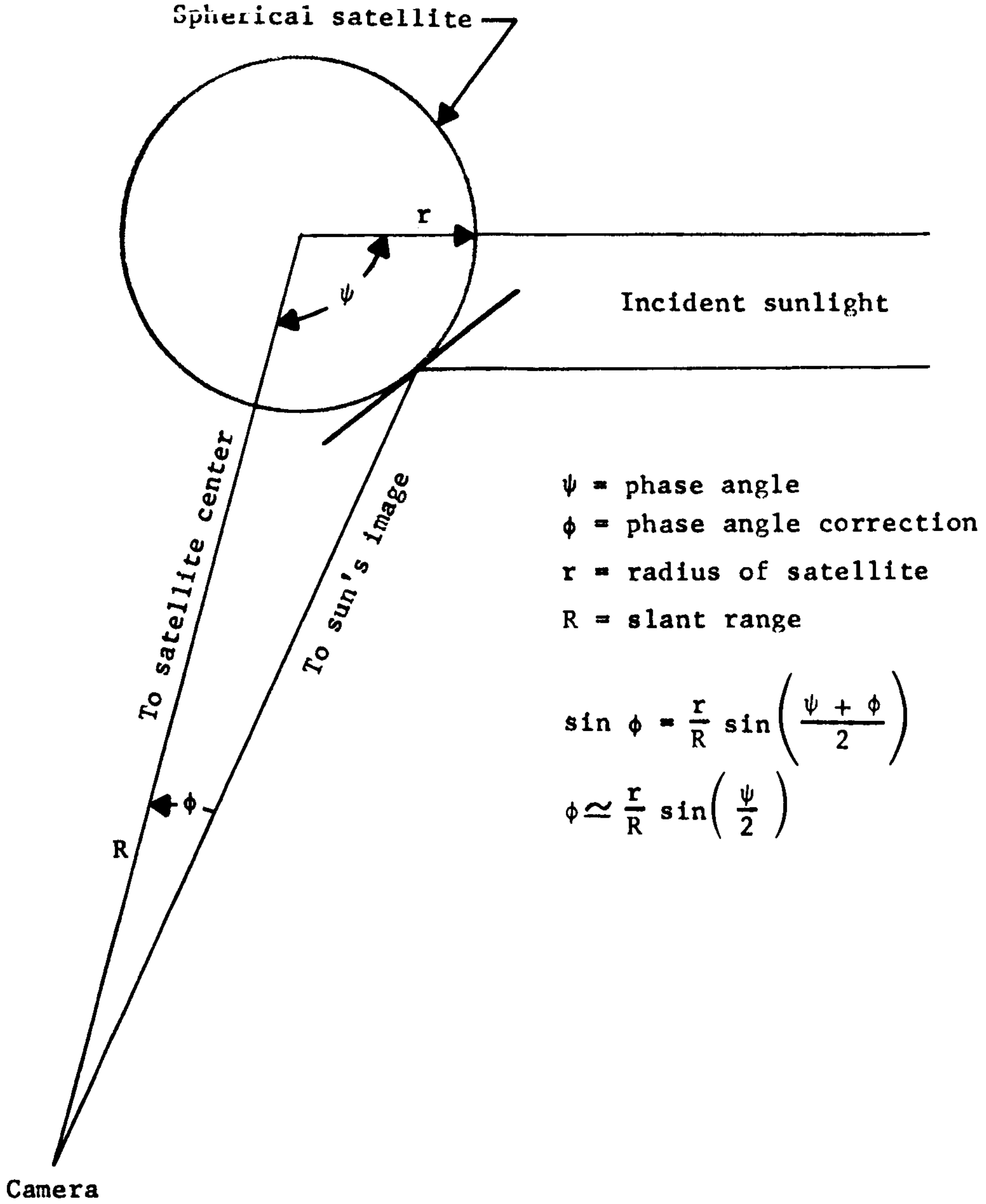


Figure C-7.- Phase angle correction for specular reflection.

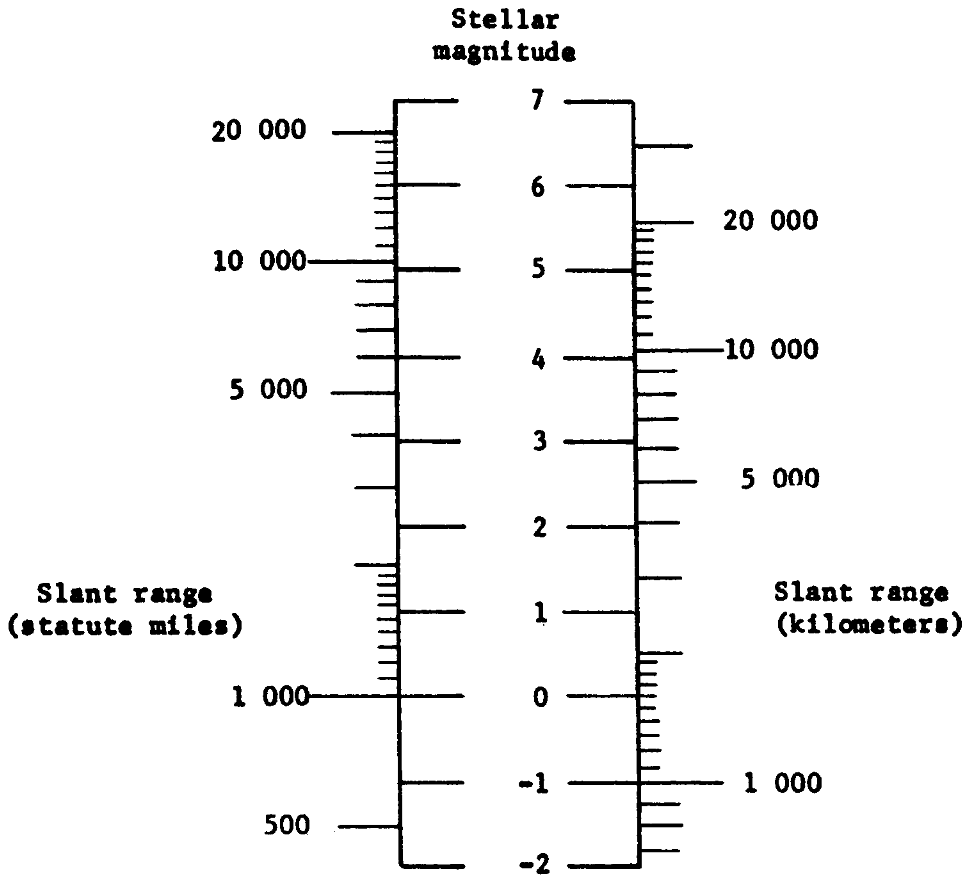


Figure C-8.- Stellar magnitude as a function of slant range for PAGEOS.

Launch

The PAGEOS spacecraft was launched from the United States Western Test Range on June 23, 1966. A two-stage thrust-augmented Thor (TAT)-Agena D vehicle carried the spacecraft into an approximately 4250 kilometer (2294.8 n. mi.), 87° prograde, circular orbit (fig. C-9). Some of the significant events of the launch trajectory are given in figure C-10. Shortly after insertion into orbit, the canister was spring-ejected from the second stage of the vehicle at a low velocity. When a separation distance of about 500 feet (152 m) had been attained, a pyrotechnic device separated the canister halves and allowed the folded sphere to be inflated by the subliming compounds and the residual gases.

Satellite inflation occurred over Madagascar. Optical coverage of the event was provided by SAO-Olifantsfontein, MOTS-Johannesburg, the Boyden Observatory at Bloemfontein, and MOTS-Tananarive. The orbital ephemeris will be established hereafter by the SAO and MOTS networks. Figure C-11 is an approximate suborbital plot of the launch trajectory and the first three orbits of PAGEOS, and indicates an orbital period of about 3 hours.

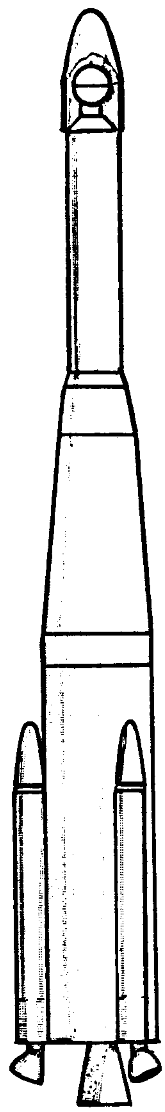


Figure C-9.- PAGEOS spacecraft mounted on top of launch vehicle.

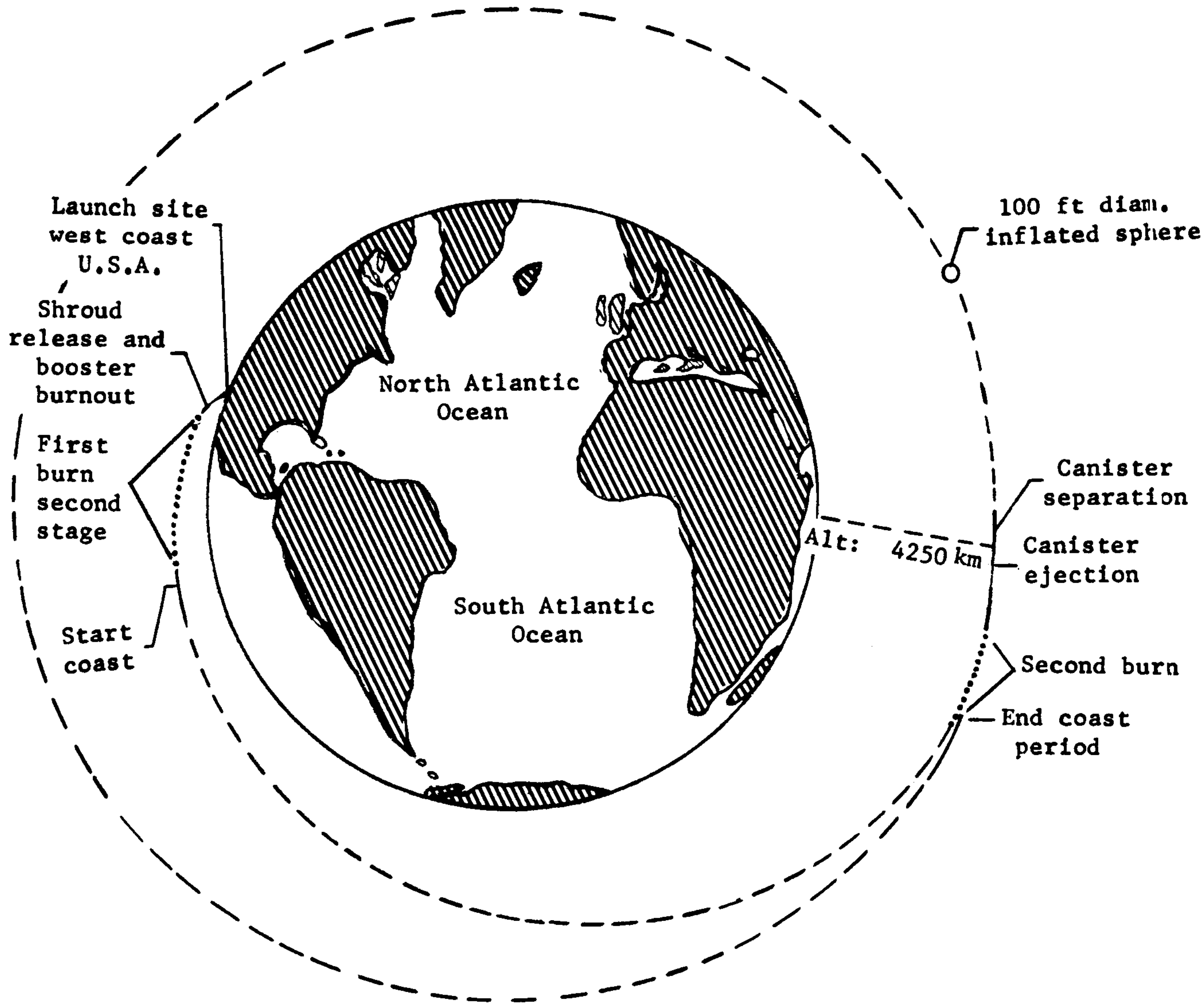


Figure C-10.- PAGEOS spacecraft launch events.

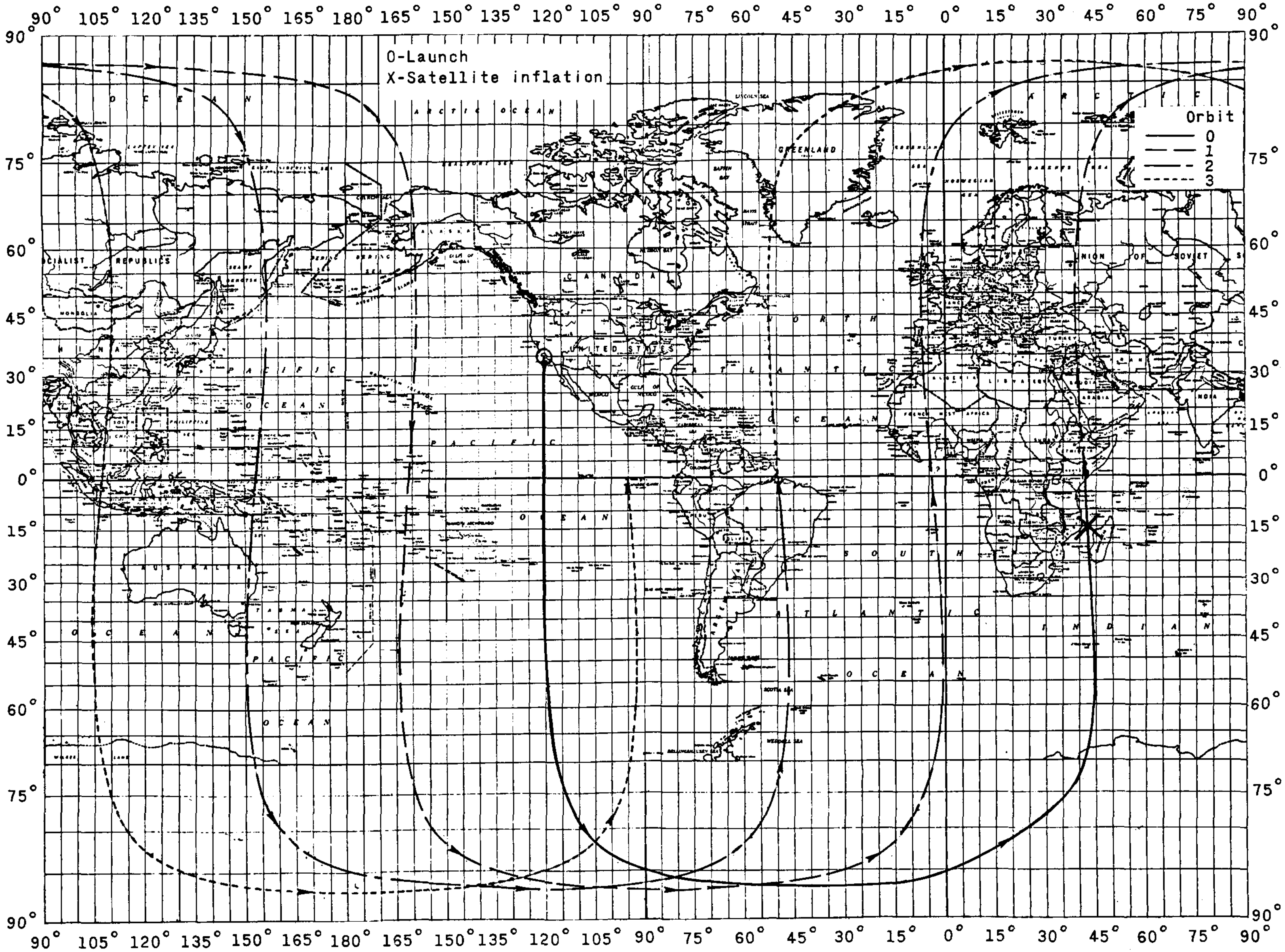


Figure C-11.- Predicted suborbital plot of PAGEOS for first three orbits.

D. ORBIT CHARACTERISTICS

Orbit Selection

To satisfy the requirements of the original 36-station network, PAGEOS had to be placed in a near-polar orbit with an altitude around 4000 (2159.8 n. mi.) to 4500 kilometers (2429.8 n. mi.). The high area/mass ratio of the satellite makes it sensitive to solar-radiation pressure and thus the given altitude-inclination region was investigated to assure a minimum orbital lifetime of 5 years.

References to the original literature on the influence of solar-radiation pressure on artificial satellites can be found in reference 10. In general, orbital motion is dependent upon the perturbations of the argument of perigee and the right ascension of the ascending node (see fig. D-1), and the relationship of the major axis of the orbit to the earth-sun line. The simplified presentation of the PAGEOS orbit is intended only to explain the general nature of the dependence of the launch right ascension on the launch date. For a more complete explanation, a review of the literature is necessary.

The stability of certain orbital parameters of PAGEOS within the range 80° to 100° inclination and 4000 to 4500 kilometers (2159.8 to 2429.8 n. mi.) altitude has been analyzed (refs. 11 and 12) with a modified version of the "Lifetime 18" computer program originally developed by A. J. Smith, Jr., and R. A. Devaney of the NASA-Goddard Space Flight Center. The modified program updates the orbital elements on a daily basis. Since the Harris-Priester atmospheric density model used in the original program requires over 3 hours of computer time to analyze one initial orbit for a 5-year period, a simplified model was substituted to permit a rapid analysis of many possible orbits.

When the modified program was tested on the orbit of the Echo I satellite, the program made the best estimate of the satellite's behavior with the atmospheric density assumed to be zero. The predicted variations in the orbital elements were slightly larger than those for the real case. Since the atmospheric drag is not considered to be significant until near the end of PAGEOS' life (atmospheric drag and solar pressure are equal at approximately 800 km (432 n. mi.)), the results of the study are considered to be quite realistic.

The most significant effect of solar-radiation pressure expected on a low density satellite is to introduce eccentricity to the orbit to an extent dependent on the rotation of both the plane of the orbit and the major axis (defined by the argument of perigee) with respect to the earth-sun line. A resonant condition, whereby the eccentricity will build up and reduce the lifetime, can occur when the major axis either remains fixed with respect to the sun direction or rotates in the orbital plane at the same rate that the sun rotates in and out of the orbital plane. The first case results in a monotonic increase in

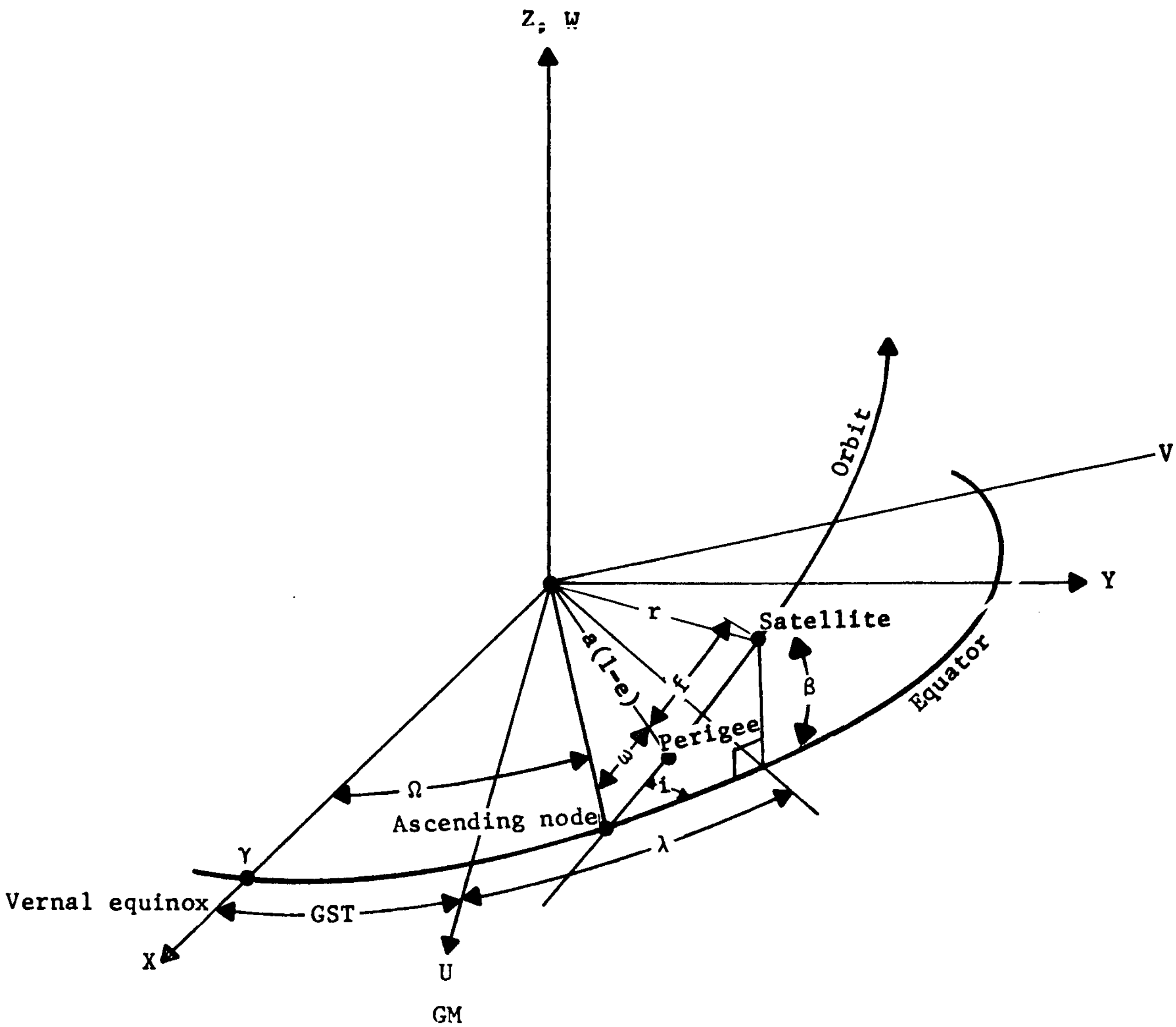


Figure D-1.- Orbit and coordinate systems.

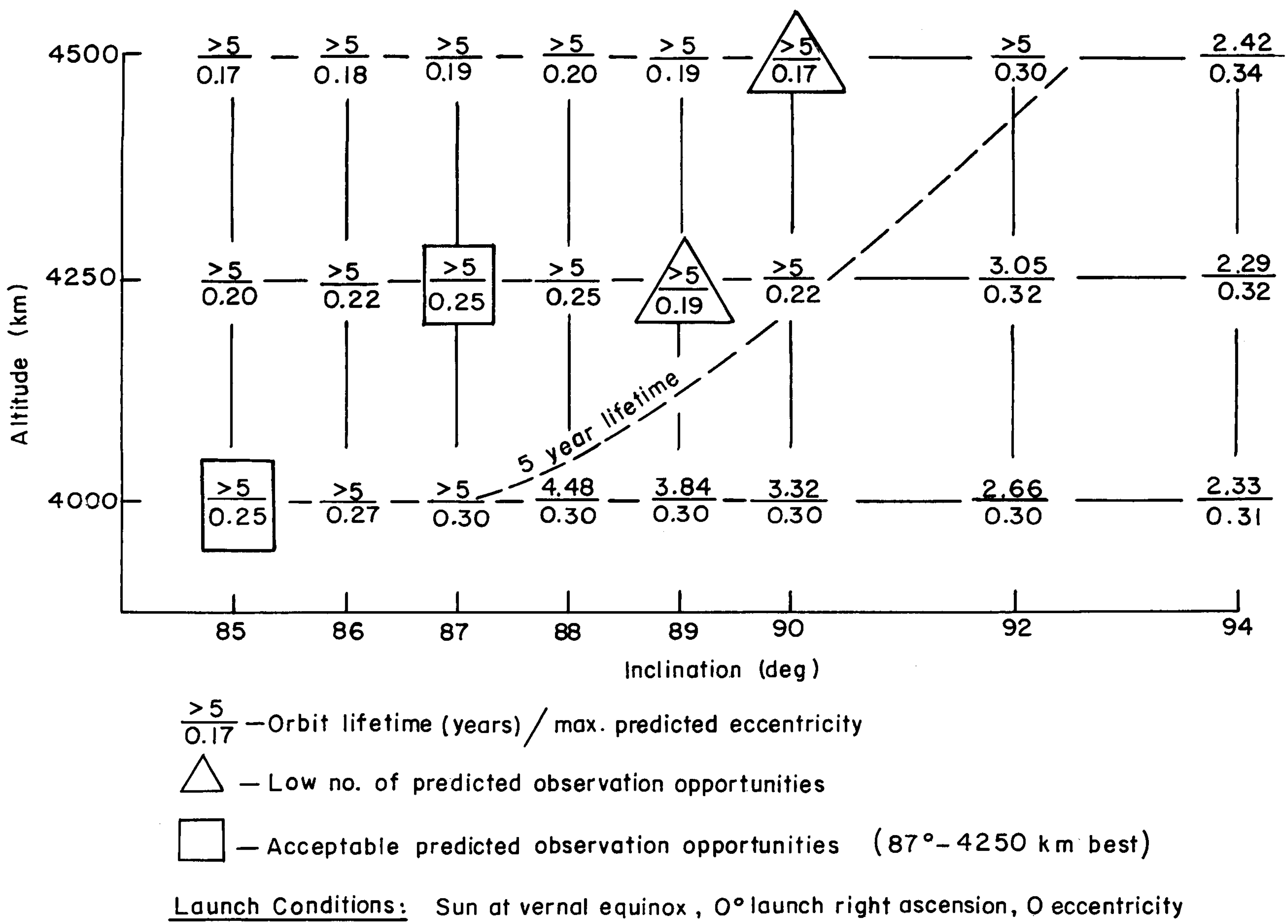


Figure D-2.- Orbit lifetime and eccentricity buildup as a function of initial altitude and inclination.

eccentricity. The second case, which occurs in near-polar orbits, results in an oscillating stairstep increase in eccentricity. A satellite in a near-resonant orbit will behave in a similar manner, except that the eccentricity will periodically increase and then decrease.

In near-polar orbits the major axis of the orbit of an Echo-type satellite rotates about a degree per day against the direction of satellite motion (refer to fig. D-1). If the sun is assumed to be at the vernal equinox and a right ascension of the initial ascending node of 180° is assumed, a circular orbit will have a perigee induced over the South Pole. The major axis will rotate northward toward the sun at the same time the sun is moving northward at its greatest rate. This "in phase" condition will cause the eccentricity to increase. Six months later when the sun is at the autumnal equinox, the perigee is located over the North Pole (a rotation rate of the major axis of about a degree per day being assumed), and will move southward toward the sun while the sun is moving southward at its greatest rate. As long as this "in phase" condition exists, the eccentricity will periodically increase.

With a launch right ascension of 0° a nonresonant condition will occur and the satellite can be expected to have a near maximum lifetime. With the sun at the vernal equinox and 0° right ascension of the initial ascending node, the lifetime of orbits within the above region were predicted (fig. D-2). All the orbits were assumed to have an initial eccentricity of near zero. Less than 5 years lifetime was predicted for 88° at 4000 kilometers (2159.8 n. mi.), 92° at 4250 kilometers (2294.8 n. mi.), and 94° at 4500 kilometers (2429.8 n. mi.); that is, increasing inclination and decreasing altitude approaches a resonant condition. These results are, in general, in harmony with the data reported in the review article by Polyakhova (ref. 10).

Within the inclination range of 85° to 90°, four possible orbits 85°, 87°, 89°, and 90° were analyzed for observation opportunities. The 85°, 89°, and 90° orbits had the lowest eccentricity buildup at these altitudes. The high inclination orbits indicated poor station coverage, whereas the 87°, 4250-kilometer (2294.8 n. mi.) orbit was the most satisfactory and was thus selected for the PAGEOS mission.

Variation of Orbital Elements

The predicted 5-year maximum eccentricity of the PAGEOS orbit is dependent upon the launch time of day. The launch time determines the right ascension of the initial ascending node, which defines the orientation of the sun line relative to the orbital plane. Since a 5-year life is critical to the success of the PAGEOS program, a plot of the variation of predicted eccentricity buildup with the initial right ascension was generated with the use of the modified "Lifetime 18" program. A plot was made for the first day of each month of the year to determine if a 1-year launch calendar was feasible. A composite of

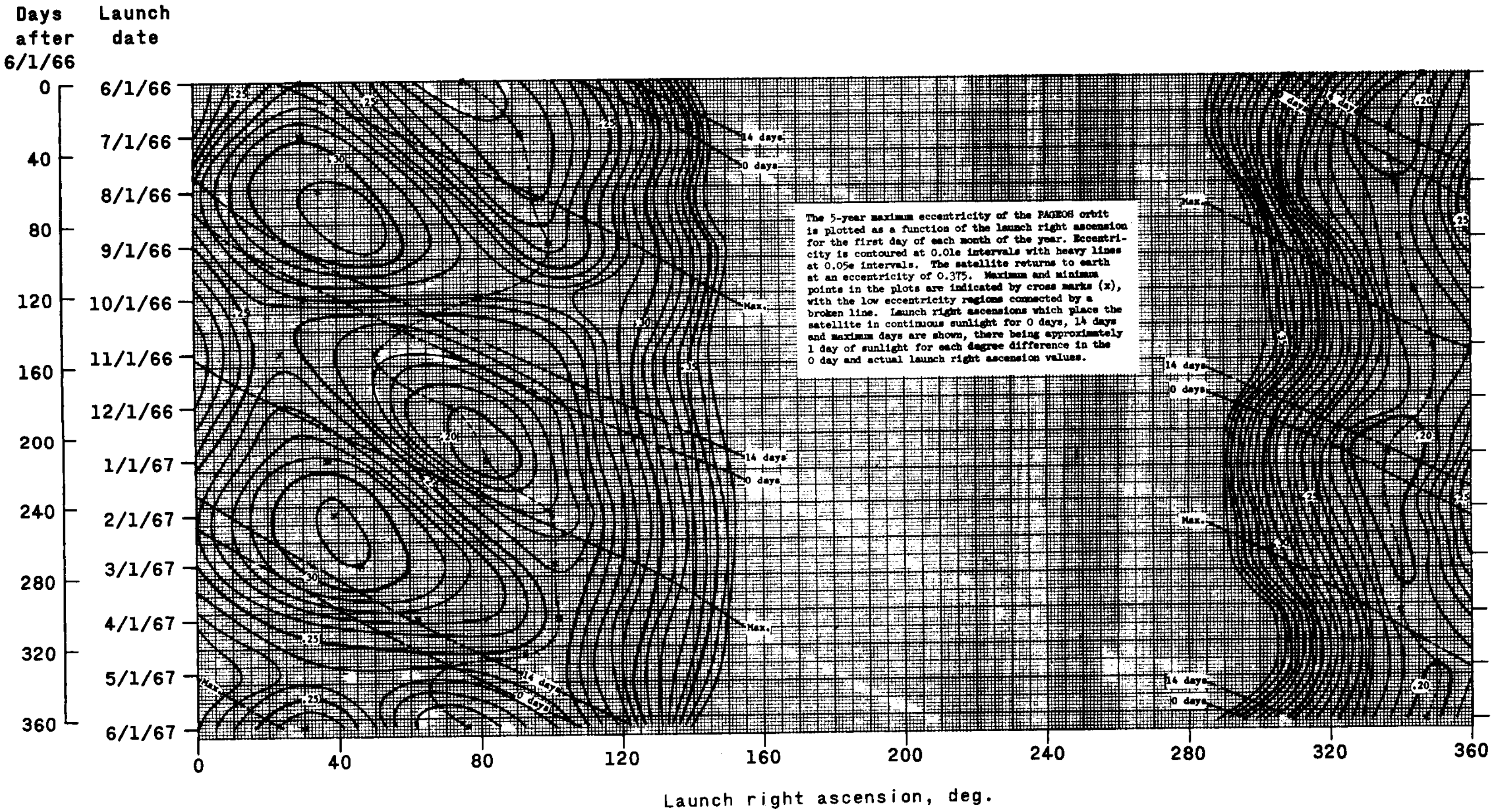


Figure D-3.- Maximum eccentricity versus launch right ascension as a function of the launch date.

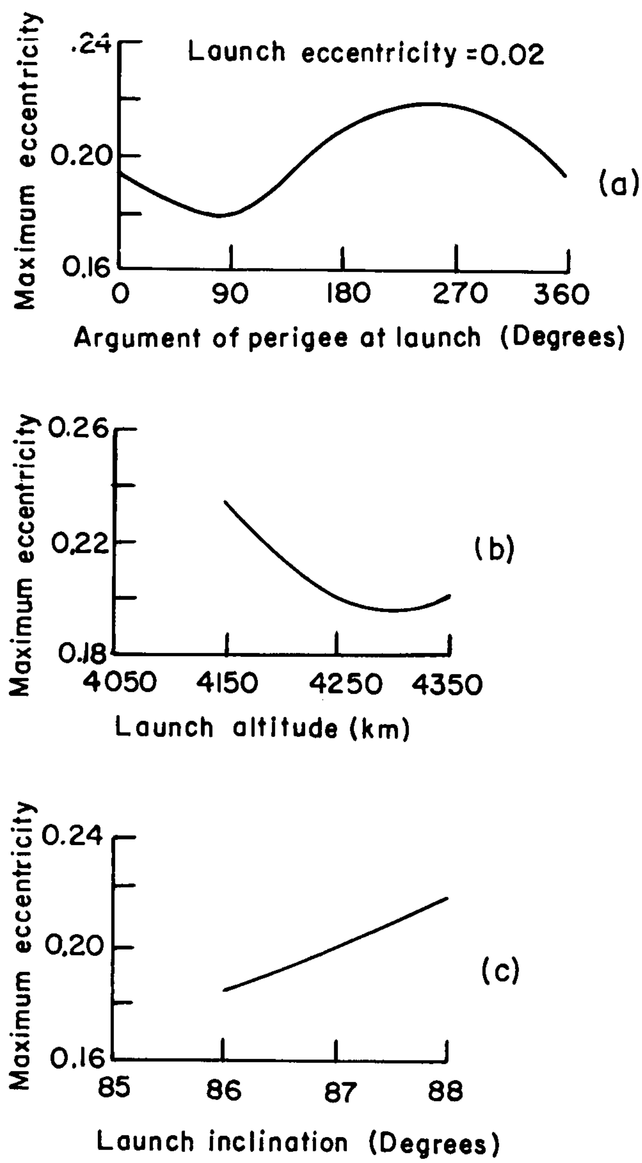


Figure D-4.- Error induced eccentricity variations.

this information is given in figure D-3, where the 5-year maximum eccentricity is plotted as a function of the launch date and initial right ascension.

The region of lowest eccentricity is around 345° launch right ascension. Another region of low eccentricity occurs around 90°. The relative insensitivity of these regions, as well as the less than 5-year lifetime zone, to the launch date is partially due to the 5-year nature of the plot. A lesser time interval could begin to show a dependence on the launch date.

Two additional constraints must be considered in defining the launch time:

(1) The satellite must initially be in continuous sunlight for a period of 14 days to ensure proper inflation.

(2) A 1-hour launch window is desirable.

The sunlight requirement is satisfied when the launch right ascension lies within the 14-day to maximum-day points indicated in figure D-3. It is apparent that the best times of year to launch are May-June and November-December (periods of lowest eccentricity). When the sunlight requirement forces a change from 345° to the 90° region, an eccentricity buildup of about 0.27 is possible.

Before an acceptable 1-year launch calendar can be established, it is necessary to evaluate the increase in eccentricity due to possible unfavorable launch errors in the nominal orbital elements. Figure D-4 shows the influence of eccentricity, altitude, and inclination errors at orbit injection on the 5-year eccentricity buildup. If an injected eccentricity of 0.01 with a 270° argument of perigee, a 50-kilometer (27 n. mi.) loss in altitude and a 1/4° increase in inclination are assumed, the predicted 5-year maximum eccentricity may be as high as 0.3, with a resultant minimum perigee altitude near 1000 kilometers (539.95 n. mi.). Since the Echo I satellite has been as low as 1000 kilometers (539.95 n. mi.) at perigee, this value is not considered to seriously affect the lifetime of the satellite. Thus a 1-year launch calendar is permissible.

Figures D-5 to D-8 show the predicted variations with time of the semimajor axis, eccentricity, inclination, and argument of perigee and right ascension for the PAGEOS orbit. Figure D-9 shows the predicted altitude variations after launch. It is possible to remove part of the accumulated 5-year eccentricity by placing a favorable argument of perigee in the orbit at launch (ref. 11). This condition was not considered necessary for PAGEOS since a satisfactory orbit can be obtained with zero initial eccentricity.

Observation Predictions

Viewing opportunities for the 36 stations (table D-I) in the C&GS proposed network are predicted for a 5-year period based on a June 1, 1966, launch date. In this analysis an acceptable simultaneous observation was subject to the following conditions:

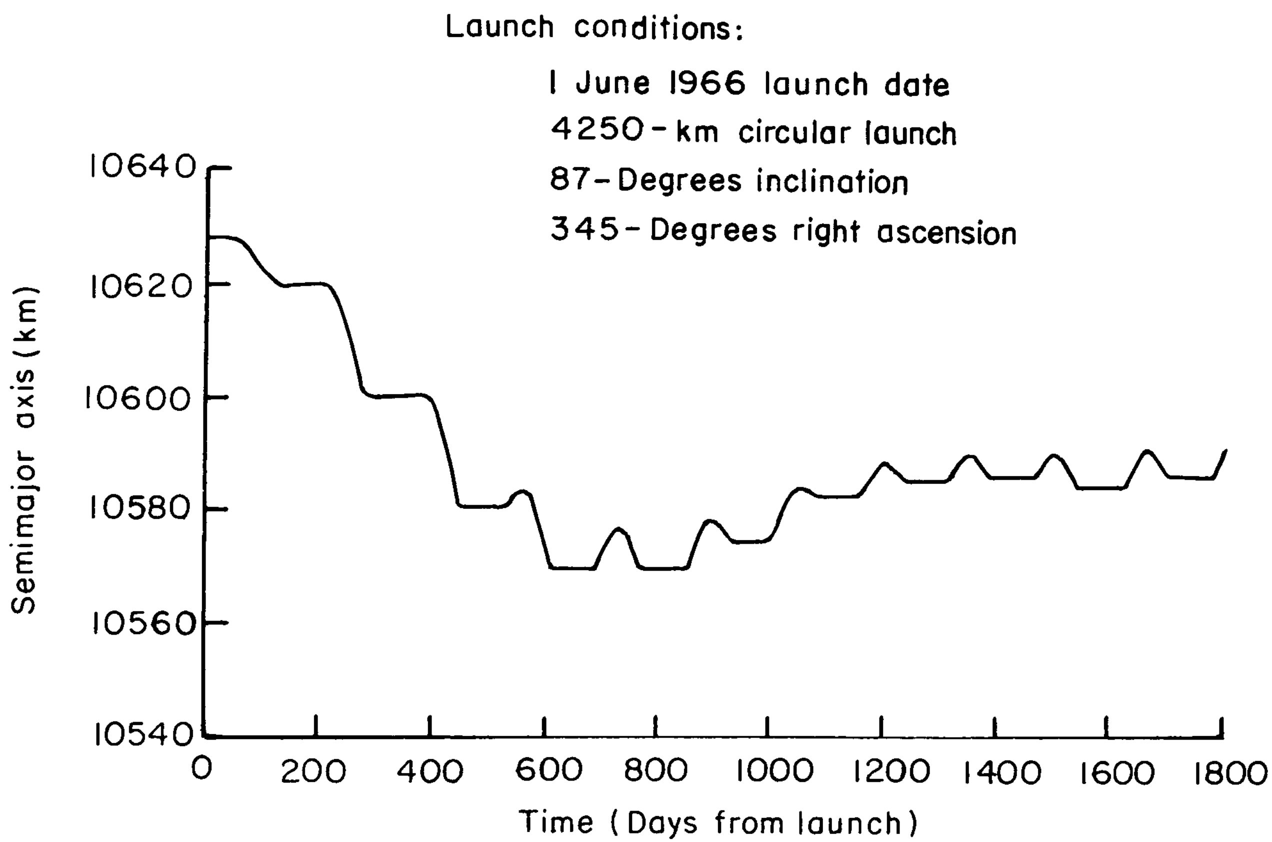


Figure D-5.- Predicted semimajor axis as a function of time after launch.

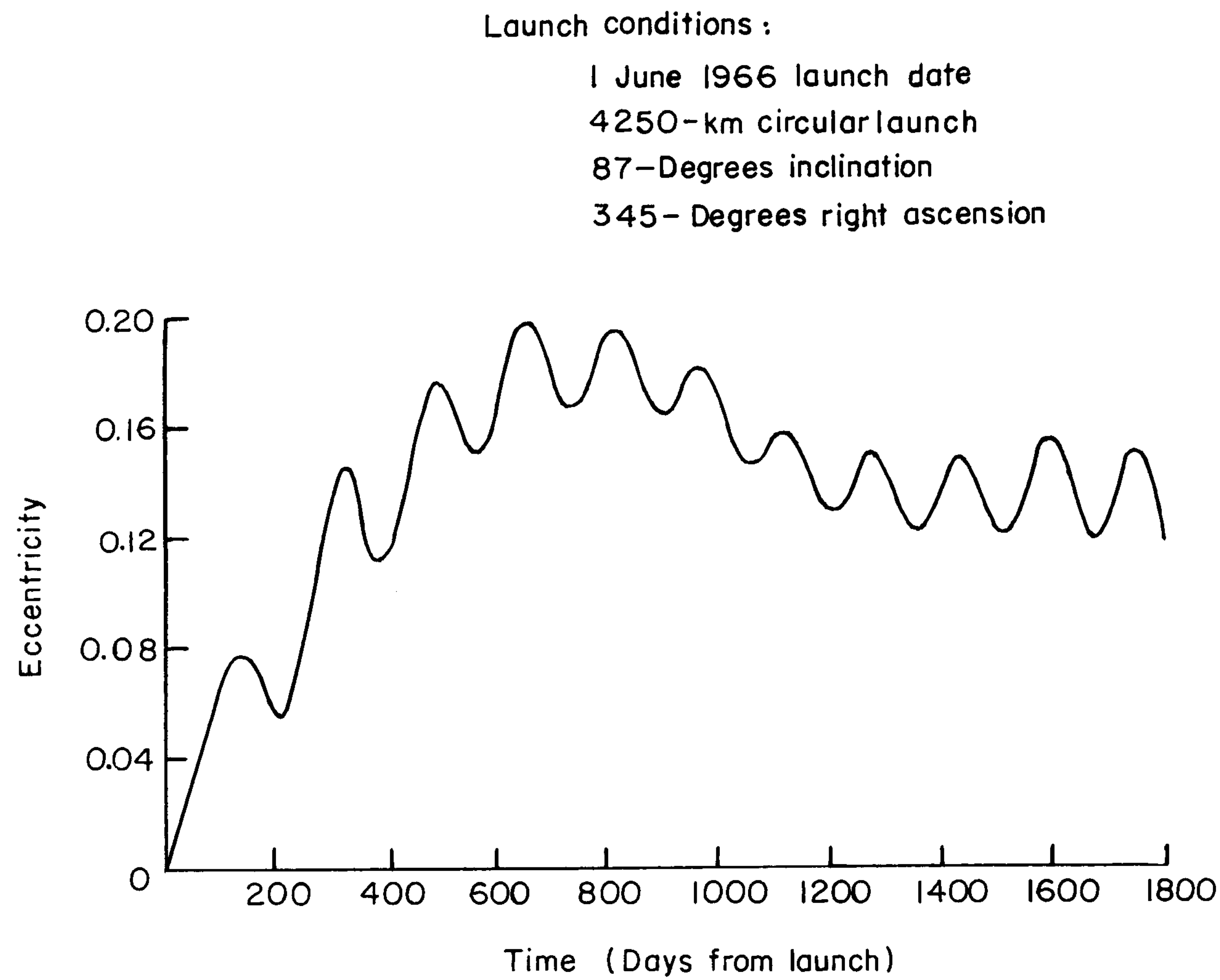


Figure D-6.- Predicted eccentricity as a function of time after launch.

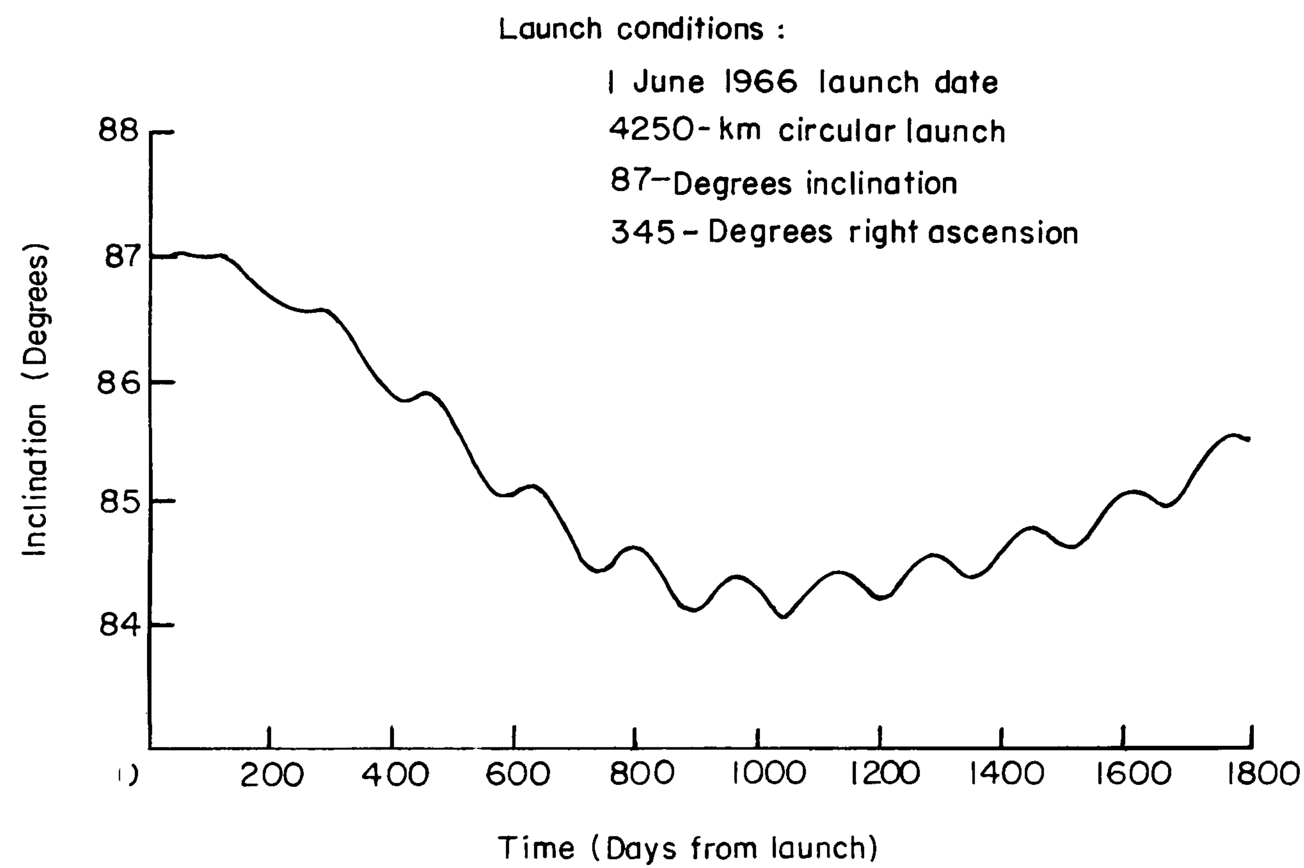


Figure D-7.- Predicted inclination as a function of time after launch.

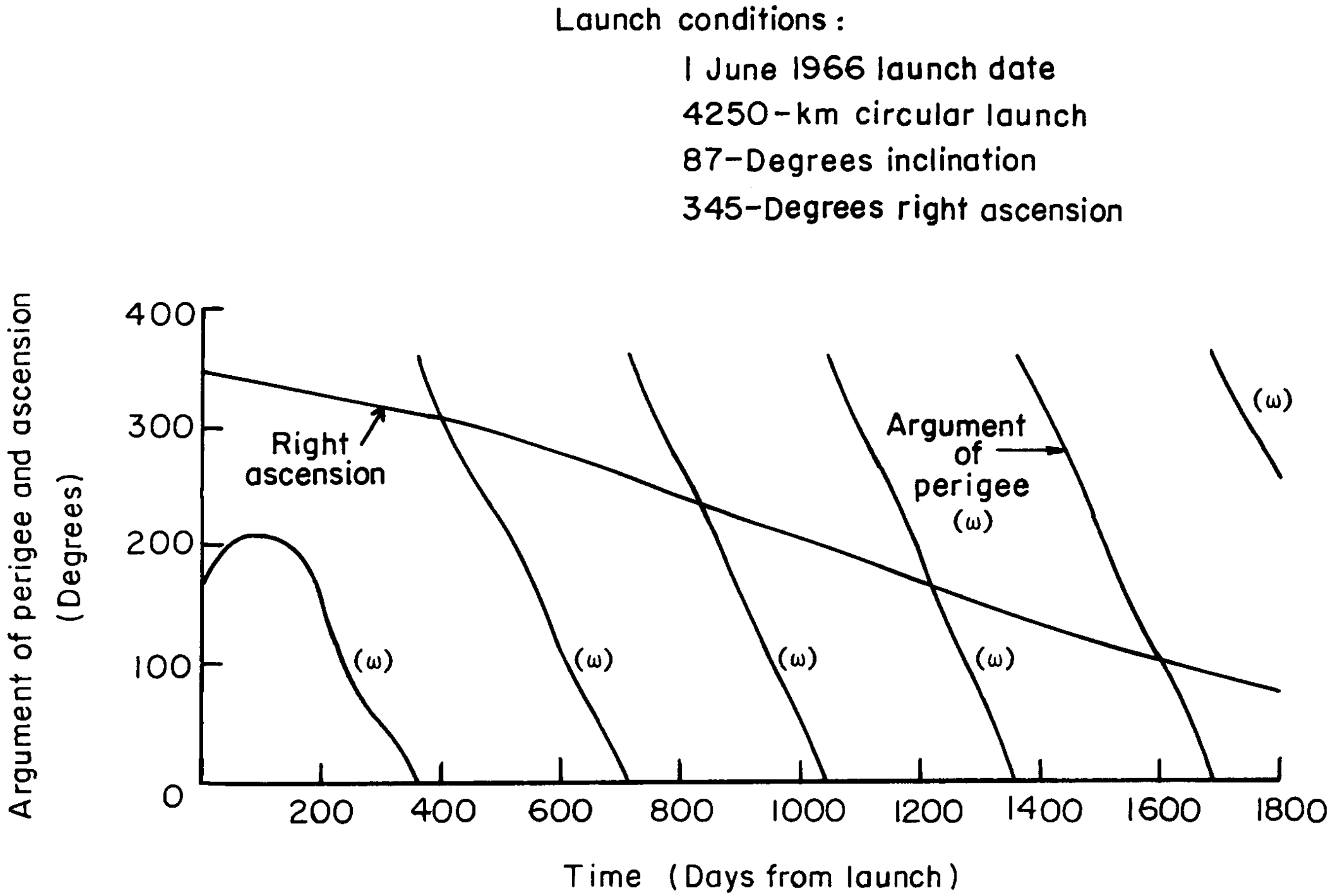


Figure D-8.- Predicted argument of perigee and right ascension as a function of time after launch.

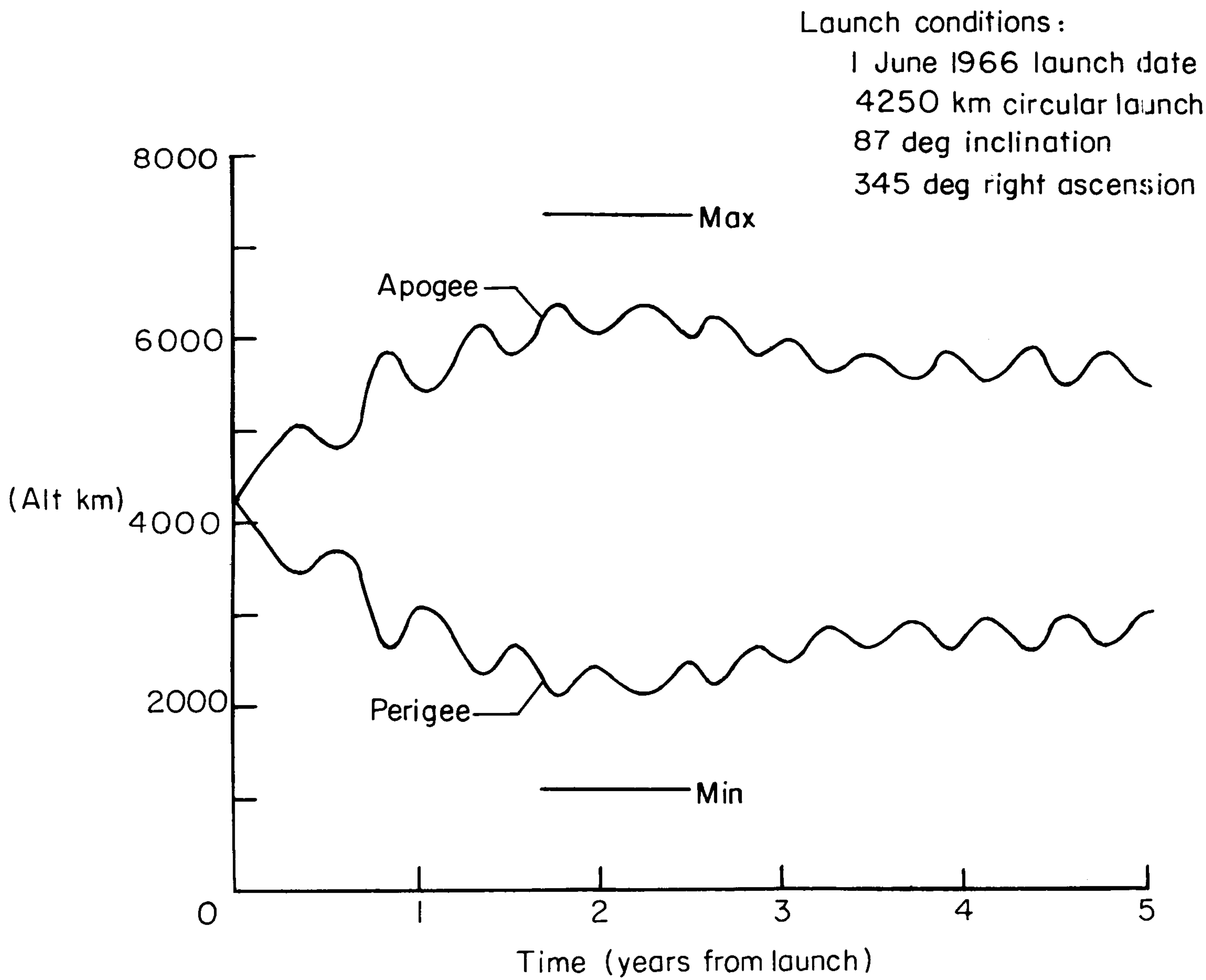


Figure D-9.- Predicted PAGEOS altitude as a function of time after launch.

(1) The viewing stations must be in astronomical darkness (that is, sun at least 18° below horizon).

(2) The station-satellite elevation angle must be at least 30°.

(3) The satellite altitude must not exceed 5000 kilometers (2700 n. mi.).

(4) The viewing conditions must be acceptable at two or three stations simultaneously for a period of at least 2 minutes.

A map of the 36-station network (fig. D-10) records the total 5-year viewing opportunities for each base line and triangle, where the 3-station observations are included in the base line observations.

A 2-year calendar of the base line observation only (appendix IV) reveals the dependence of the viewing opportunities on the season and the right ascension of the orbital plane. The 3-station observations generally occur during the periods of maximum base line observations.

In section B it was noted that at least two simultaneous observations should be made from a given base line such that two planes are generated with an intersection angle greater than 60°. An indication of this condition can approximately be inferred from the number of 3-station observations shown on each side of the base line in figure D-10.

The best observation intervals occur before the satellite has reached its maximum eccentricity (about 2 years after launch). The low coverage in the equatorial region is due to the satellite's entrance into the earth's shadow zone when it is over these stations. The long east-west equatorial base lines are the most critical in this respect.

A relaxation of the observation conditions (that is, lower elevation and higher altitude conditions) may improve the situation somewhat, although a dramatic change is not expected. A more probable approach will be an increase in the number of stations and a reorientation of the base lines to increase the observation opportunities. However, regardless of the changes made in the network this observation analysis will still reflect the general trends in viewing opportunities.

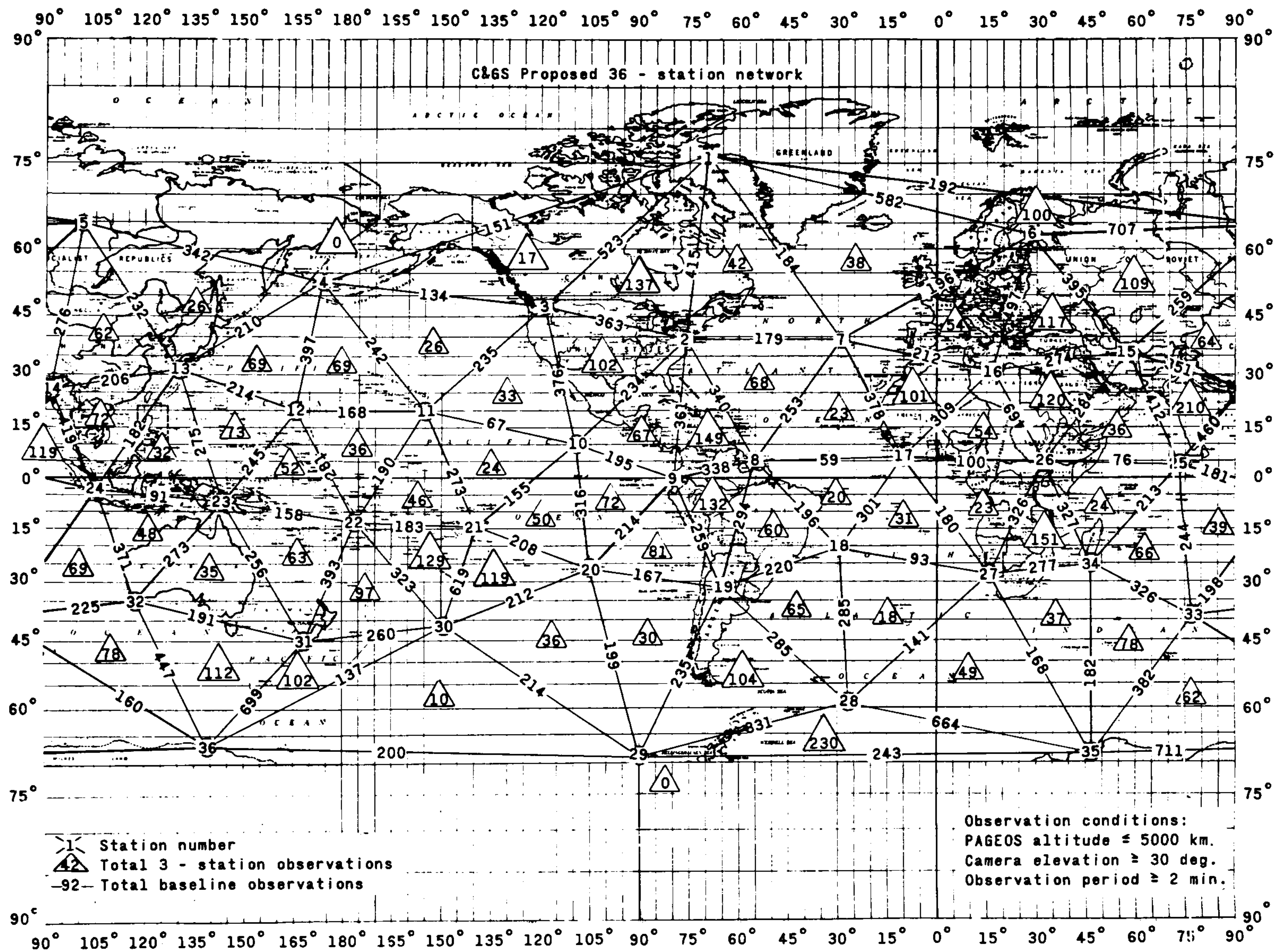


Figure D-10.- Predicted 5-year simultaneous observations of PAGEOS for 2 and 3 stations.

TABLE D-1.- STATION LOCATIONS FOR PROPOSED 36-STATION NETWORK

	Station	Latitude, deg	Longitude, deg
1	Greenland, Thule AFB	76.5 N	68.7 W
2	U.S.A., Aberdeen, Md.	39.5 N	76.1 W
3	U.S.A., Larson AFB, Wash.	47.2 N	119.3 W
4	U.S.A., Aleutian Is., Shemya I.	52.7 N	174.1 E
5	U.S.S.R., Tura, Siberia	64.8 N	101.0 E
6	Finland, Kuopio	62.7 N	28.0 E
7	Azores Is., Pico I.	39.0 N	28.5 W
8	Dutch Guiana, Paramaribo	05.5 N	55.2 W
9	Equador, Quito	00.1 S	78.5 W
10	Clipperton I.	10.3 N	109.2 W
11	U.S.A., Hilo, Hawaii	19.8 N	155.0 W
12	Wake Island	19.7 N	166.2 E
13	Japan, Kagoshima	31.7 N	130.6 E
14	India, Gauhati	26.2 N	91.7 E
15	Iran, Sabzawar	36.5 N	57.5 E
16	Libya, Syrte	31.7 N	16.4 E
17	Liberia, Roberts Field	06.8 N	10.2 W
18	Trindade Island	20.5 S	29.4 W
19	Argentina, Villa Dolores	32.0 S	65.1 W
20	Sala y Gomez Island	26.6 S	105.2 W
21	Pukapuka Island	14.7 S	138.8 W
22	Wallis Is., Uvea I.	13.2 S	176.3 W
23	New Guinea, Kikori	07.3 S	144.2 E
24	Sumatra, Palembang	03.0 S	105.0 E
25	Maldive Is., Male´	04.2 N	73.3 E
26	Sudan, Juba	04.8 N	31.6 E
27	Southwest Africa, Bogenfels	27.8 S	15.8 E
28	So. Sandwich Is., Saunders I.	58.4 S	26.7 W
29	Antarctica, Peter I.	69.2 S	90.0 W
30	So. Pacific Ocean, Shoal	41.5 S	148.6 W
31	New Zealand, Queenstown	45.0 S	168.2 E
32	Australia, Denmark	35.0 S	117.3 E
33	St. Paul Island	38.7 S	77.0 E
34	Madagascar, Fort Dauphin	25.0 S	47.1 E
35	Antarctica, U.S.S.R. Station	68.0 S	46.4 E
36	Antarctica, France Station	67.0 S	139.0 E

E. REQUIREMENTS FOR DATA COLLECTION AND REDUCTION

Photographic Requirements

The aim of photographic data collection and reduction is to approach the limiting accuracy of the satellite triangulation technique, considered to be about 0.3 to 0.5 second of arc error in the determination of the satellite's direction. (See refs. 6 and 13.) Only one available camera lens has been specifically designed for this application – the 450-mm BC-4 lens. (See ref. 14.) Since the data analysis program can correct for many of the camera-induced errors, it is possible to obtain equivalent results with cameras designed for other applications, such as aerial reconnaissance (when adapted with chopping shutters, etc.). With this point in mind, table E-I lists a general set of camera specifications, suitable for PAGEOS satellite photography, with which one can expect to approach this limit. A discussion of several important camera characteristics and their influence on the image formation follows (ref. 15):

Astigmatism and spherical aberrations.- Both astigmatism and spherical aberrations leave a symmetrical image, and thus are of secondary importance only.

Coma.- One of the basic requirements for satellite triangulation is good point-image photography. Coma tends to distort the image and makes a measurement of the ideal image point difficult. It undoubtedly accounts for a major portion of the camera error and, therefore, should be minimized.

TABLE E-I.- GENERAL CAMERA SPECIFICATIONS FOR PAGEOS SATELLITE TRIANGULATION PHOTOGRAPHY

A camera system falling within the specifications outlined below should be suitable for triangulation photography with the PAGEOS satellite.

Focal length	300 to 1000 mm
Aperture	100 to 200 mm
Field of view	10° to 20°
Lens aberrations	Good point-imaging essential; that is, coma and chromatic aberration should be minimized. A certain amount of distortion and curvature of field are relatively harmless as they can be corrected by data analysis.
Plate size	18 cm × 18 cm × 6 mm and larger, depending on focal length
Shutter speed	Variable – 0.01 sec to 2.0 sec
Exposure timing accuracy	200 microseconds or better for 1:1,000,000 accuracy

Distortion.- Distortion acts to displace the image. It can partially be determined by test photography, however, and as long as the circle of least confusion (ref. 16) is symmetrical about a point, with no dependence on color or brightness of the source, the measuring procedures can recover the point and data analysis used to correct distortion will apply. Also, if the circle of least confusion is kept small enough, atmospheric-seeing variations will smooth out small asymmetries and they can be ignored. It is necessary to incorporate in the analysis sufficient parameters to describe the distortion characteristics of each individual photograph at the moment of exposure.

Field of view.- The field of view should be large enough to carry a sufficient number of stars of the proper magnitude to permit adequate data reduction (up to 150 star images for 18 cm × 18 cm (7.09 × 7.09 in.) plate with f = 300 mm (11.81 in.)) (ref. 17). When the field of view is increased, there is an increase in the number of stars required and the number of parameters required to describe the distortion characteristics of the specific photogrammetric record.

Focal length.- Increasing the focal length would help to decrease the measurement errors, but account must be taken of the faster satellite image motion across the plate and its relation to the exposure time. The BC-4 cameras will be equipped with a 450-mm (17.71-in.) lens as soon as they are made available, to replace the 305-mm (12.01-in.) lens now in use. From a cost and portability viewpoint, the focal length should be no longer than operating and measuring considerations require.

Aperture.- Increased aperture could reduce the atmospheric effect (shimmer), but this reduction would apply to satellite images only since star images are averaged over a period of time. At the C&GS, shimmer is dealt with by statistical means, that is, by producing and measuring a large number of satellite images. A practical limit for refracting optics is about 200 mm; above this value the distortion becomes excessive, and reflecting optics should be used.

Field curvature.- A flat field is desirable in that a conventional two-screw measuring machine can be used. Although rectangular photographic plates are universally available, it is not necessary to utilize all the plate. It is general practice to limit the field to the area within the inscribed circle on the plate or even less.

Exposure time as a function of aperture.- Exposure times will influence camera characteristics, long exposures requiring less critical lens specifications. The maximum angular motion of stars is 15 seconds of arc per second of time; with satellites the maximum angular motion is about ten times this value. For a 1-second-of-arc accuracy, the minimum exposure time then should be about 1/15 second for stars and 1/150 second for satellites. The exposure time and aperture are usually varied to produce images which are compatible with the measuring techniques.

Minimum image size.- Satellite images should be small enough to be measured accurately on the measuring machine, but not so small as to be outside the range of resolution allowed by present-day photographic emulsion grain sizes. The desirable image size for measurement is about 30 to 40 microns (refs. 15 and 18). For a 20-micron measuring mark, a 40-micron image size is obtained by the C&GS BC-4 cameras with 1/60 second exposure at f/8, when the slant range of Echo I is about 1700 kilometers (ref. 18). At shorter ranges the f-stop is changed to f/11.

Timing Requirements for Simultaneous Observations

When a satellite carries a flashing light (such as GEOS), the only timing requirements placed on the cameras recording the event are those associated with the star background which do not require simultaneity. For a continuously illuminated passive satellite, accurately timed chopping shutters must be employed to break the satellite's trail into many images which are appropriately coded to ensure positive identification. To obtain a one-part-per-million accuracy (ref. 19) with a satellite range of 1500 kilometers (809.94 n. mi.), the midopening of all chopping shutters must be timed to about 200 microseconds with respect to a common time standard.

Phase Angle Correction

The satellite triangulation method requires that two or more cameras simultaneously photograph a common source of light against a star background. Because of the highly specular surface of the PAGEOS sphere, the sun's image will be displaced from the satellite's center toward the sun by an amount dependent on the phase angle (camera-satellite-sun angle), and thus no two cameras will photograph identical positions on the sphere. A correction must therefore be applied to refer effectively all images to a common origin.

The phase angle correction given in figure C-7 will adjust the computed satellite direction measurements to the center of the sphere, and will yield geometrically consistent data from all camera stations. Of course, this correction applies only to spherical satellites with highly specular reflecting surfaces, such as PAGEOS and Echo I.

Refraction and Light Path Corrections

Excellent agreement has been established between theoretical and observed values for the astronomical refraction correction (ref. 18). The station latitude, temperature, and pressure are used to make this correction. To test the validity of the theoretical model, it is the general practice to take a zenith angle photograph at the station.

For a satellite outside the atmosphere, the image can be treated as astronomical refraction minus a differential refraction, or parallactic angle. (See refs. 20 (sec. 2.4) and 21.) Since the refraction anomaly varies with elevation angle, it is appropriate to correct each satellite image individually. As an example, the differential refraction correction (normal atmospheric conditions being assumed) for a 1000-kilometer-high (539.96 n. mi.) satellite at an elevation angle of 30° is about 1 second of arc. Standard astronomic reduction procedures for stars are applicable. (See the Supplement to the American Ephemeris and Nautical Almanac (ref. 22).)

Because of the dynamic nature of the satellite's orbit, it is justified to assume that its motion is smoother than can be reconstructed from the individual images recorded during the photographic event. When the timing accuracy is sufficiently high to be disregarded as a primary source of error (less than 200 microseconds), the X and Y coordinate measurements of the images, after correction for lens distortion, and so forth, may be least-squares fitted to a high-order polynomial in time to smooth the random errors introduced by the measuring process and the atmospheric shimmer effect (ref. 17). A single fictitious satellite observation can then be generated from each simultaneous photographic record.

A time correction must be made to account for the differences in the light path from the satellite to each camera recording the event; for example, a difference in range of 300 kilometers (161.99 n. mi.) introduces a millisecond error. This correction can be made by adjusting the time of the fictitious observations to refer all satellite positions to the same point in space.

It is then apparent that the midopening of all chopping shutters need not be synchronous; it is only important to know accurately the corrections necessary to refer them to a common time standard.

F. TYPICAL EXPERIMENTAL FACILITIES

C&GS Modified Type BC-4 Camera

The BC-4 stellar-oriented fixed-camera tracking system was originally developed by the Ballistic Research Laboratories, Aberdeen Proving Ground (BRL/APG) to obtain missile trajectory data, and thus they are called ballistic cameras. The C&GS modification of this system has been optimized for satellite triangulation; for example, range-timing circuitry has been eliminated and the chopping shutter rate is slower. Although there are several different ballistic cameras in operation in the United States (refs. 20 (sec. 2.3) and 23) such as the PC-1000 and the PC-600, only the BC-4 has been widely employed in passive satellite triangulation and it will be the primary source of data collection during the PAGEOS program. A brief description of the salient features of the C&GS BC-4 system follows (refs. 3 and 24).

Optical properties.- The BC-4 camera consists basically of a modified Wild RC-5 aerial camera mounted on a modified lower part of the Wild T-4 astronomical theodolite (fig. F-1). Three different lens cones are presently available: the 115 mm Aviogon, the 210 mm Aviotar, and the 305 mm Astrotar (recommended for satellite triangulation). A 450-mm lens will eventually replace the 305-mm lens now used in the C&GS system. (Two C&GS cameras are currently operational with the 450-mm lens.)

The Astrotar lens has an aperture of 117 mm and an iris diaphragm which can be stopped down to f/32. Exposures are taken on precision glass plates $215 \times 190 \times 6$ mm with an effective picture size of 180 mm by 180 mm, corresponding to a field of view of 33° by 33°. (The field of view is less with the 450-mm lens.) Stars of magnitude 8 and 9 are readily identified on the plate, although stars of magnitude 6 and 7 are preferred because of the higher accuracy of the star catalog information.

The camera is used in a fixed position; its initial orientation in azimuth prior to the observations is made with a field adjustment frame by sighting through the principal point eyepiece to an azimuth light. Azimuth and elevation settings are made accurate to about 10 seconds of arc. The horizontal axis is leveled with a striding level which has a sensitivity of 6 seconds per 2 mm division.

Shutters.- Three rotating disks used for chopping satellite trails are located between the lenses next to the plane of the iris diaphragm. Two of these disks counterrotate and are high-speed exposure shutters, while the third, a slow disk, is used as a capping disk to limit the exposure rate (fig. F-2). The disks are driven by a high-precision gearing system. A 500-cps synchronous motor maintains constant speed, the drive signal being supplied by a time-code generator which is regulated by a high-precision quartz crystal oscillator. Reduction gearing permits the exposure disks to be rotated at selected primary rates of 10, 5, or 2.5 times per second corresponding to exposure durations of

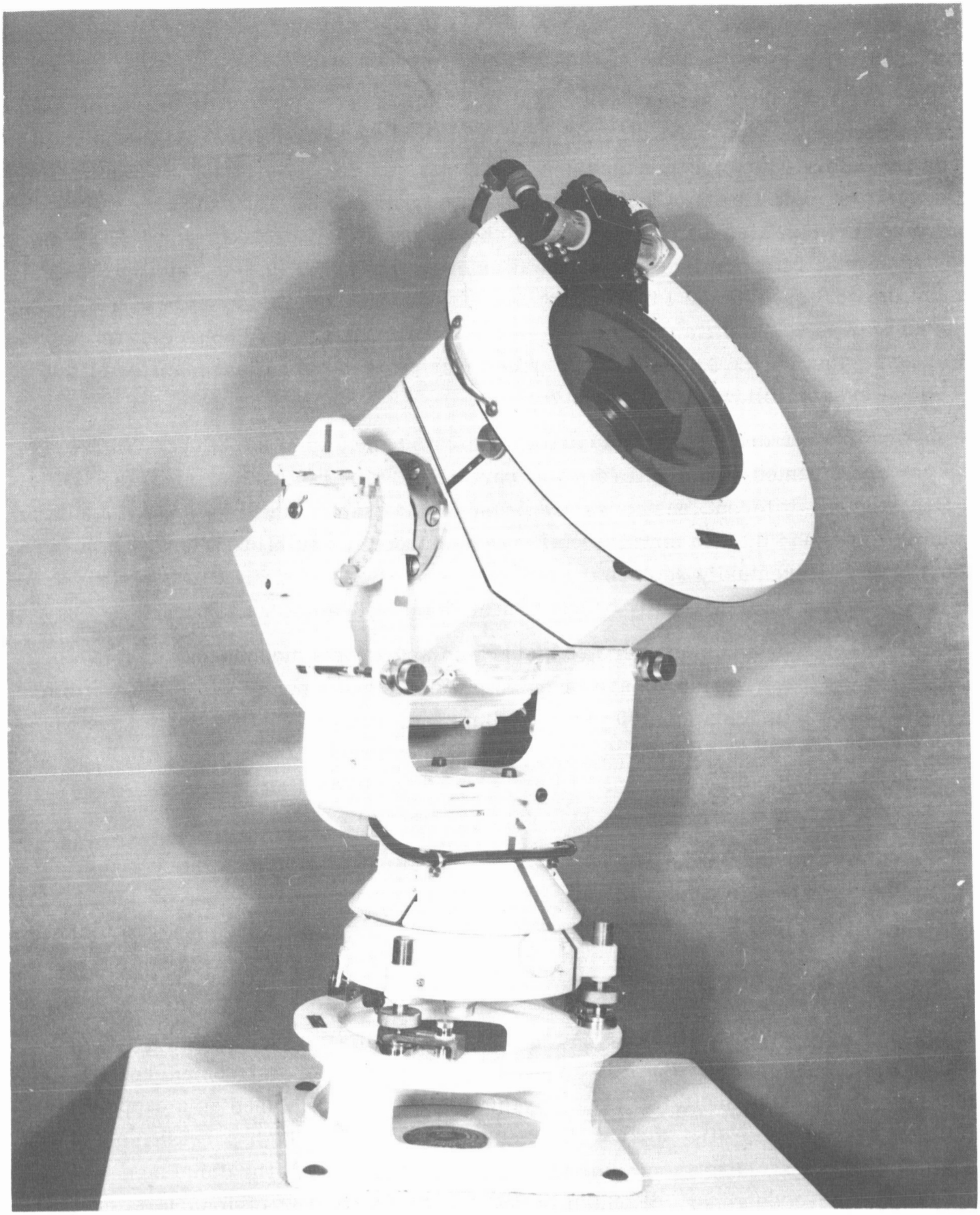


Figure F-1.- Wild BC-4 satellite tracking camera.

1/60, 1/30, and 1/15 of a second, respectively. The capping disk is synchronized with the exposure disks to reduce the exposure rate by ratios of 2 or 5. Further reduction of the exposure rate and coding of the satellite trail are accomplished by the auxiliary capping shutter mounted in front of the camera lens (fig. F-1). This is an iris-type shutter that can be programed to divide the exposure rate by 2, 4, 8, or 16.

The auxiliary capping shutter is used primarily to chop star trails before and after the satellite is tracked. This information is used to determine the orientation of the camera and provide a check on the stability during the entire observation period. The closed duration of the shutter can be varied to accommodate the angular motion of the stars in the portion of the sky to which the camera is directed. For instance, a 2-second break may be optimum for an equatorial star, whereas a 30-second break may be required for a star in the vicinity of the celestial pole. For star trail observations, the disk shutters are automatically locked in the midopen position.

A normal star trail consists of several groups of five images each. Different exposure times are used for each group to optimize the image size and quality depending upon the star's magnitude and declination. In this way the stellar images as well as the satellite images are made compatible with the measuring mark, and the problem of personal bias is greatly reduced.

It is possible to operate the auxiliary capping shutter such that star trails can be effectively chopped even during the satellite observation.* Thus, in future work, the C&GS will establish an additional calibration during the recording of the satellite images.

Electronic timing equipment.- The C&GS timing method can be considered in three phases: (1) initial setting of the local time standard (station clock) of each camera station with respect to the common time standard (master clock), (2) determination of the daily drift rate of the station clock with respect to the master clock, and (3) determination of the relationship between the station clock and the shutter midopen times (jitter).

The master clock is a highly stable quartz crystal oscillator maintained by the National Bureau of Standards at Beltsville, Maryland. This oscillator has a frequency stability of a few parts in 10^{-11} and is maintained to within -149.5×10^{-10} and $+150.5 \times 10^{-10}$ of the nominal frequency of cesium.

A portable crystal clock is used to transport time from the master clock to set each of the station clocks. Its oscillator has a frequency stability of better than $\pm 1 \times 10^{-10}$ and a frequency drift rate of less than 1×10^{-10}. When synchronized with the master clock, experience indicates that the portable clock will normally have an uncertainty of less than ± 10 microseconds after a 5-day field trip.

*Personal communication with Eugene Taylor of C&GS.

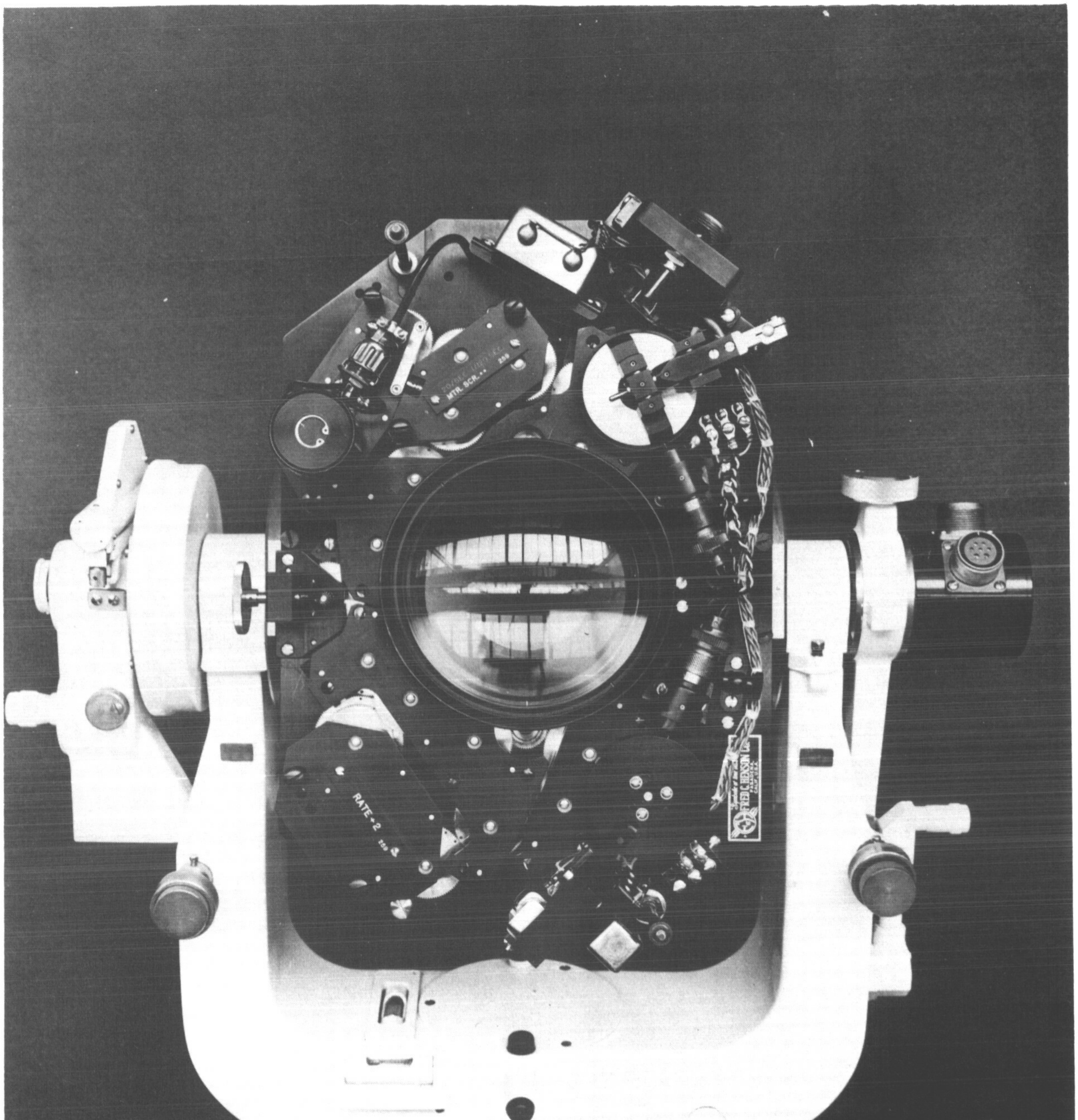


Figure F-2.- BC-4 shutter-drive mechanism.

Each station clock is equipped with a time-code generator which derives a 100-kilocycle-per-second frequency from a precise crystal oscillator having the same specifications as the portable clock. Time corrections for the oscillator could be calculated from results of regular trips of the portable clock, if cost and logistics considerations permitted it.

However, the use of VLF transmission provides a practical and accurate method for determining day-to-day time variations. The major disadvantage of VLF (very low frequency) for time pulse determinations is the inherent slow rise time of the VLF pulse, a difficulty which is overcome with the use of the portable clock. A VLF phase comparator is used constantly to compare the oscillator frequency with one of several VLF carrier frequencies. The phase of the VLF carrier waves is highly stable, and in spite of a diurnal variation of about 40 microseconds, it will return to within about 2 microseconds of the same value after each 24-hour period. In practice, two VLF phase comparators, timed to different frequencies, are employed to check timing results and to provide a continuous record in the event reception from one station is interrupted.

The electronic synchronization system (fig. F-3), which is commercially available, provides means for synchronizing the time-code generator to a common time standard, synchronizing the disk shutters to the time-code generator, remotely operating both shutter systems, exposing the fiducial marks and other camera identifying information, and producing a detailed record of the observational program on 10 channels of the paper recording tape.

The desired disk-shutter rate is established electronically by the programer-selector switches and mechanically in the camera by the selection of gear blocks. Program-timing pulses from the time-code generator trigger the oscilloscope at the rate established on the programer unit. This rate must correspond with one of the following exposure rates established in the camera: 1 pp2s (1 pulse per 2 seconds), 1 pps, 1.25 pps, 2.5 pps, or 5 pps. The shutter-gate timing pulse from the time-code generator is displayed on the oscilloscope and establishes the acceptable limits between which the midopen position of the shutters must occur. Pulses from the camera indicating the midopen position are also displayed on the oscilloscope and can be adjusted by means of the phase synchronizer to fall in the center of the gate; a $\pm$100-microsecond gate is considered to be adequate, but the gate can be widened or narrowed as desired.

Small mechanical and electronic disturbances (jitter) in the gearing system result in slight variations in the intervals between the pulses from the camera. However, as long as the fast-disk, shutter-open pulses occur within the shutter gate, the system is considered to operate in synchronization and all exposures are acceptable. For any pulse occurring outside the shutter gate, the corresponding exposure is positively identified on the paper recording tape as being out of synchronization limits, and the exposure will

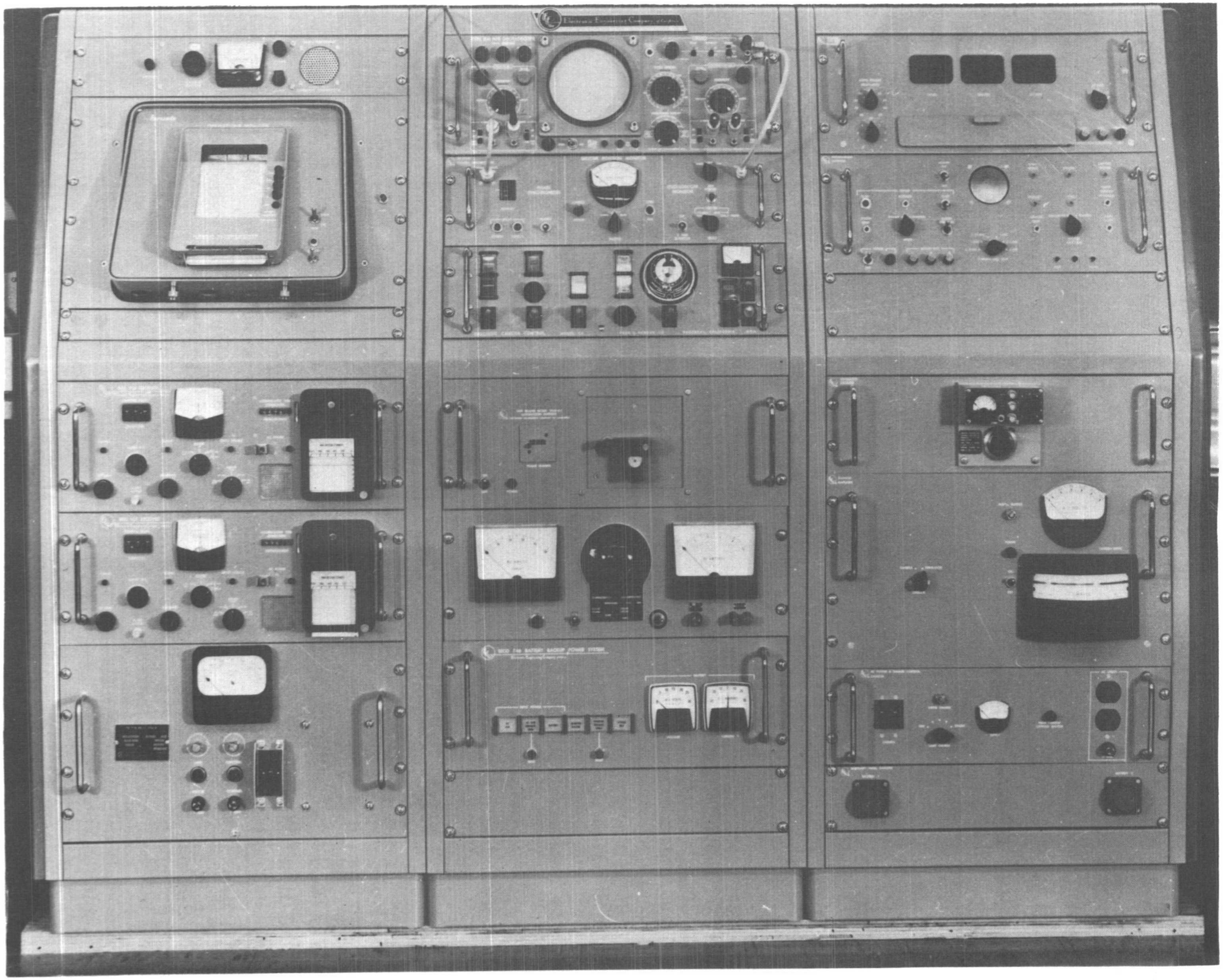


Figure F-3.- Electronic synchronization system.

later be rejected in the data reduction. The time jitter has recently been reduced to less than ±10 microseconds (ref. 14); the amount of jitter can be monitored on the oscilloscope during the observations.

In summary, the total uncertainties in the timing are: ±10 microseconds in the initial setting of the station clock, ±40 microseconds of accumulated uncertainties in the day-to-day records, and ±100 microseconds in the gate width of the shutter. The total uncertainties are then less than ±150 microseconds. Periodic field trips with the portable clock insure that these timing accuracies are maintained.

Timing requirements for star trail observations are much less demanding, as it is only necessary to know shutter times to about ±0.05 second with respect to universal time. This accuracy is obtained with time signals received from station WWV, Beltsville, Maryland, or equivalent service. Since the portable clock is actually synchronized to the oscillator used to generate the time signals, the camera stations are, in effect, using the pretransmitted time signals of station WWV as the common time reference. For star trails, times are corrected to appropriate universal time.

Field accessories.- A specially designed astrodome (fig. F-4) is used to protect the camera, pedestal, and pier from the effects of the wind during the observations, and from the heat of the sun during the day. An external air-conditioner unit maintains the anticipated night temperature during the day to reduce the undesirable effects of thermal expansion in the camera and pedestal, and a dehumidifier unit protects the camera from the corrosive effects of high humidity.

Inside the astrodome, the base of the camera is secured (but not constrained) to a specially designed pedestal which attaches to a concrete pier at ground level. The pier extends into the ground several feet depending upon the type of soil encountered. The astrodome floor provides complete isolation for the camera support. It is, of course, important to establish the camera position with respect to the geodetic datum to which the observations will be referred.

When the camera station has been set up, the pedestal is completely filled with water (or an antifreeze mixture) which acts to resist temperature changes in the pedestal during the observation periods and also adds mass to the system to dampen any external shocks and vibrations. The observers do not remain in the vicinity of the camera during the observational period since the camera is remotely operated by the synchronization system located some distance away in the electronic equipment shelter (fig. F-5).

The mobile shelter, designed primarily to house the electronic synchronization system, also provides space for a darkroom, electronic repairs, office, and storage. The unit can be towed by truck using a special mobility transporter which is attached to the shelter; it can be lifted by a crane or helicopter, and transported by aircraft, ship, railroad car, or flatbed truck.

Figure F-4.- Astrodome.

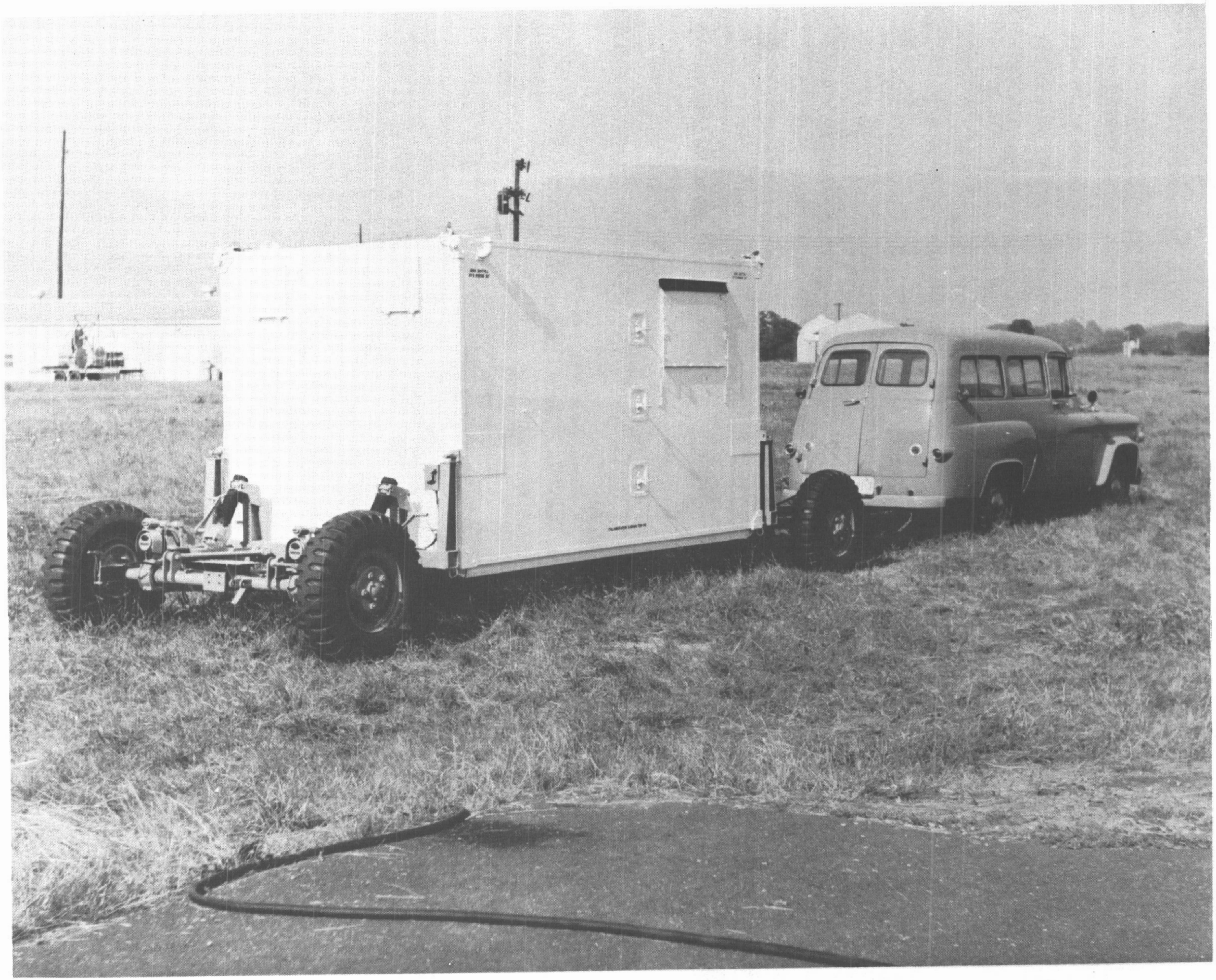


Figure F-5.- Electronic equipment shelter.

Measuring engine.- The accuracy of the satellite triangulation technique will ultimately depend upon the accuracy with which the coordinates can be established in the photogrammetric record. The measuring engines, or comparators, presently used by the C&GS feature 9- by 9-inch (22.9 × 22.9 cm) measuring stages which are manufactured with such precision that a measuring accuracy of approximately 1 micron is attainable with only linear mathematical compensation for differential measuring screw length and coordinate axis perpendicularity. High-quality optical systems provide direct binocular viewing with linear magnifications up to 40 times plate scale. A choice of reticles is possible to enable the most precise and bias-free pointings on star and satellite images.

A calibrated grid plate (refs. 3 and 17) consisting of 25 points in a 5-cm-square (1.96-inch-square) pattern is measured in each of the four primary rotational orientations by three different operators. These 12 sets of measurements are separately reduced, with corrections only for linear differential screw length and nonperpendicularity of coordinate axis being allowed. The computer program used for this reduction also makes a least-squares fit of the corrected plate measurements of the 25 grid intersection points to the true or calibrated grid values and determines the residual standard error of coordinate measurement. In this way a standard error of coordinate measurement is maintained within the range of 0.7 to 1.3 microns for all comparators.

Each comparator is equipped with an electronic readout system with typewriter and either punched card or paper tape outputs (fig. F-6).

Approximately 16 man-hours are required to reduce each plate. A set of eight drilled reference holes, about 60 microns in diameter, are made in the plate emulsion at the four corners and the midpoints of the four sides so that a continuous check can be made on the position and orientation of the photographic plate. These holes also permit the plate to be removed to allow for shift work on the comparators.

USAF PC-1000 Camera

General description.- The PC-1000 system (refs. 23, 20 (sec. 2.3), and 25) has been chosen by the U.S. Air Force as its primary observing camera for tracking active or passive satellites and for satellite triangulation. The lens was originally designed for aerial reconnaissance by Dr. James Baker. The camera has a focal length of 1000 mm (39.4 in.), an aperture of 200 mm (7.87 in.), and a $10^{\circ} \times 10^{\circ}$ field of view, maximum 14°. The image format is the same as that of the BC-4 camera, and is 180 × 180 mm (7.09 × 7.09 in.) on the standard 190 × 215 × 6 mm (7.48 × 8.46 × 0.47 in.) glass plate. Its shutter is a pulse-operated leaf type. A shutter controller and programer has the same function as that of the BC-4 camera.

Some of the field cameras are mobile units built into a trailer, and are completely self-contained and self-sufficient. In addition to the camera system, the mobile units

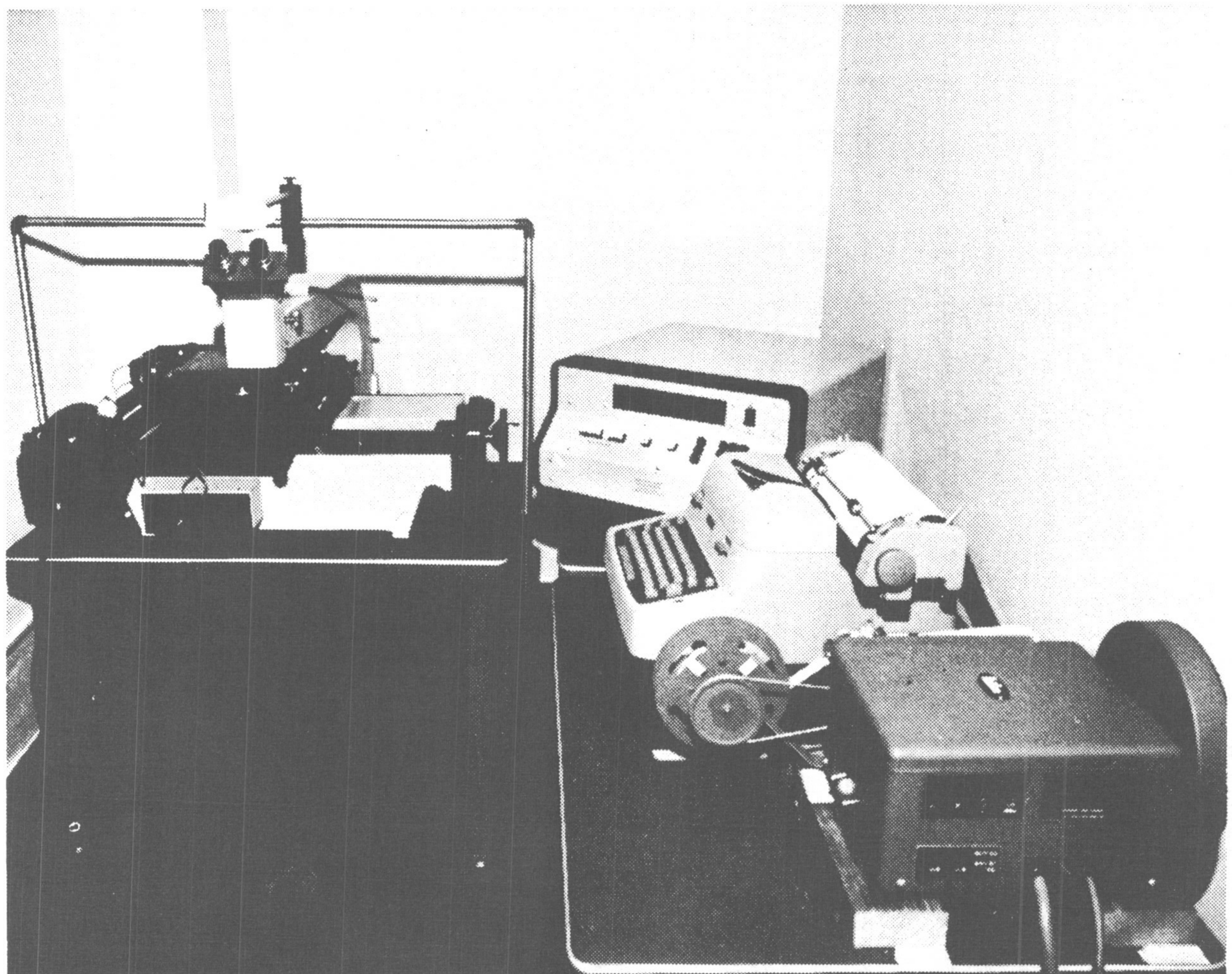


Figure F-6.- Comparator and readout equipment.

contain communications, time determination, power source, recording equipment, and capabilities of plate measurement and reduction.

Experience with ANNA.- The PC-1000 cameras have been used in various locations in the United States and other countries to obtain geodetic data from the ANNA satellite (ref. 26). The operational accuracy of the system is comparable to that of the BC-4 (i.e., 0.3 to 0.5 seconds of arc).

With regard to data collection, the PC-1000 cameras have had about the same success as the C&GS BC-4 systems. In the southeast United States, about 50 percent of the observations were lost because of weather, and approximately 23 percent were successful.

Several of the cameras are being adapted with chopping shutters for passive satellite triangulation. When completed, they might participate in the PAGEOS data collection program.

SAO Baker-Nunn Camera

The Baker-Nunn camera (ref. 20 (sec. 2.3)) (fig. F-7) has a 500-mm (19.68 in.) focal length and a 500-mm (19.68 in.) aperture (effective f/1.25). The field of view is $5^{\circ} \times 30^{\circ}$ and the photographs are made on film. The camera can either be used in the fixed mode of operation, such as that of the BC-4 and PC-1000 cameras, or in the satellite or sidereal tracking mode. In the satellite tracking mode, for instance, the 6-inch (15.24-cm) Vanguard 1 sphere was photographed at an elevation of 5000 km (2699.8 n. mi.).

The standard error of measurement in the satellite direction is about 2 seconds of arc in both right ascension and declination with the timing accurate to about 0.001 second.

The Baker-Nunn camera will be employed in the PAGEOS program to establish the SAO 12-station network. Four USAF stations will also observe PAGEOS and the data will be integrated in the SAO analysis. Two additional stations will be equipped with the new Geodetic-36 camera (fig. F-8), a modified K-50 with an f/4 lens.

NASA-MOTS Camera

The MOTS 40-inch camera is essentially a PC-1000 type, except that it is equipped with a plate-jiggling solenoid assembly used to break the trail of a passive satellite. The accuracy is 5 seconds of arc in right ascension and 2 seconds of arc in declination.

A high-speed shutter has been satisfactorily installed on one of the cameras to make it suitable for PAGEOS photography. The improved accuracy with the new shutter is about 1 second of arc in both coordinates. It is expected, however, that no more than one station will be operational before January 1967. When the stations are equipped with the new shutter, they will be integrated into the PAGEOS observation program.

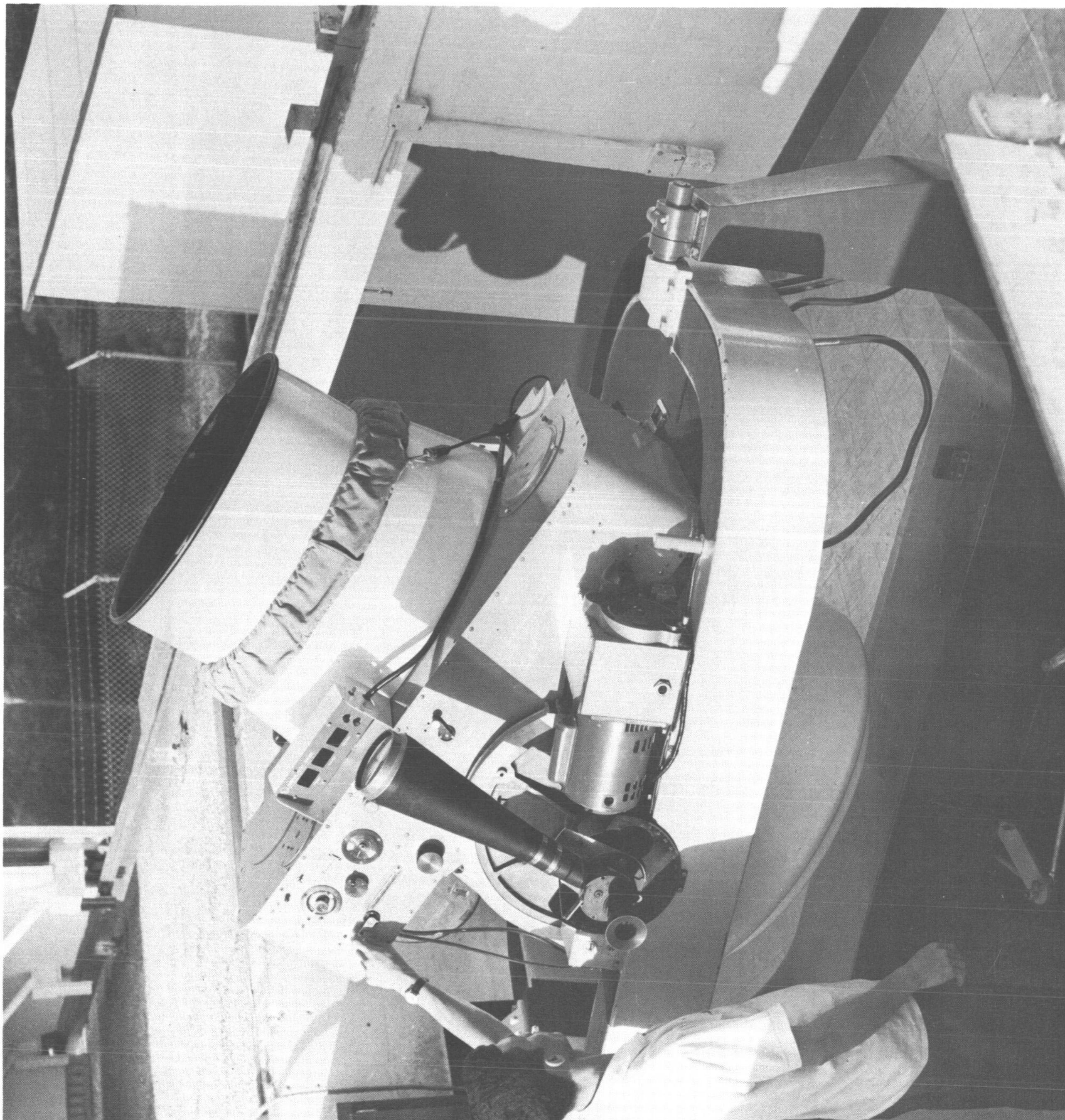


Figure F-7.- SAO Baker-Nunn camera.

Figure F-8.- SAO Geodetic-36 camera.

G. COMMUNICATIONS

Request for Participation in the National Geodetic Satellites Program

The overall responsibility for the National Geodetic Satellites Program has been assigned to the National Aeronautics and Space Administration (NASA). Within NASA, this responsibility is carried by the Office of Space Science and Applications. In general, this office is responsible for all NASA unmanned scientific satellites and the communication, navigation, and meteorological satellites, as well as for the scientific data resulting from these.

Within this office, the Space Applications Programs will provide the scientific and technical management required for the geodetic program. (See fig. G-1.) Jerome D. Rosenberg is the Program Manager.

Requests for participation in the program are evaluated on the basis of the scientific merit of the data collection and/or data analysis programs submitted by the experimenters. All requests for information about the NGSP should be addressed to:

Jerome D. Rosenberg
Code SAG
NASA
Washington, D.C.

Qualified experimenters are expected to submit preprocessed data to Geodetic Satellites Data Service on a regular basis and all data analyses must be published on a timely schedule. All observational data will be made available to qualified scientists who establish the scientific need and intent to publish.

Geodetic Operations Control Center

The Geodetic Operations Control Center (GOCC) (ref. 1) was designed and implemented by the Goddard Space Flight Center (GSFC) Project Operations Support Division to serve as the focal point for all satellite geodesy projects for which NASA has responsibility. All spacecraft operations will be coordinated with the GOCC, and all changes to operations schedules and procedures will emanate from the GOCC.

The GOCC will exercise the following operations and control responsibilities:

Coordination.- The GOCC will provide coordination, scheduling, and other operation and control information between project management and the investigations, spacecraft observers, and others who require spacecraft status.

Scheduling.- The GOCC will schedule and monitor all spacecraft activity in accordance with procedures established by the Project Office.

NATIONAL GEODETIC SATELLITE PROGRAM

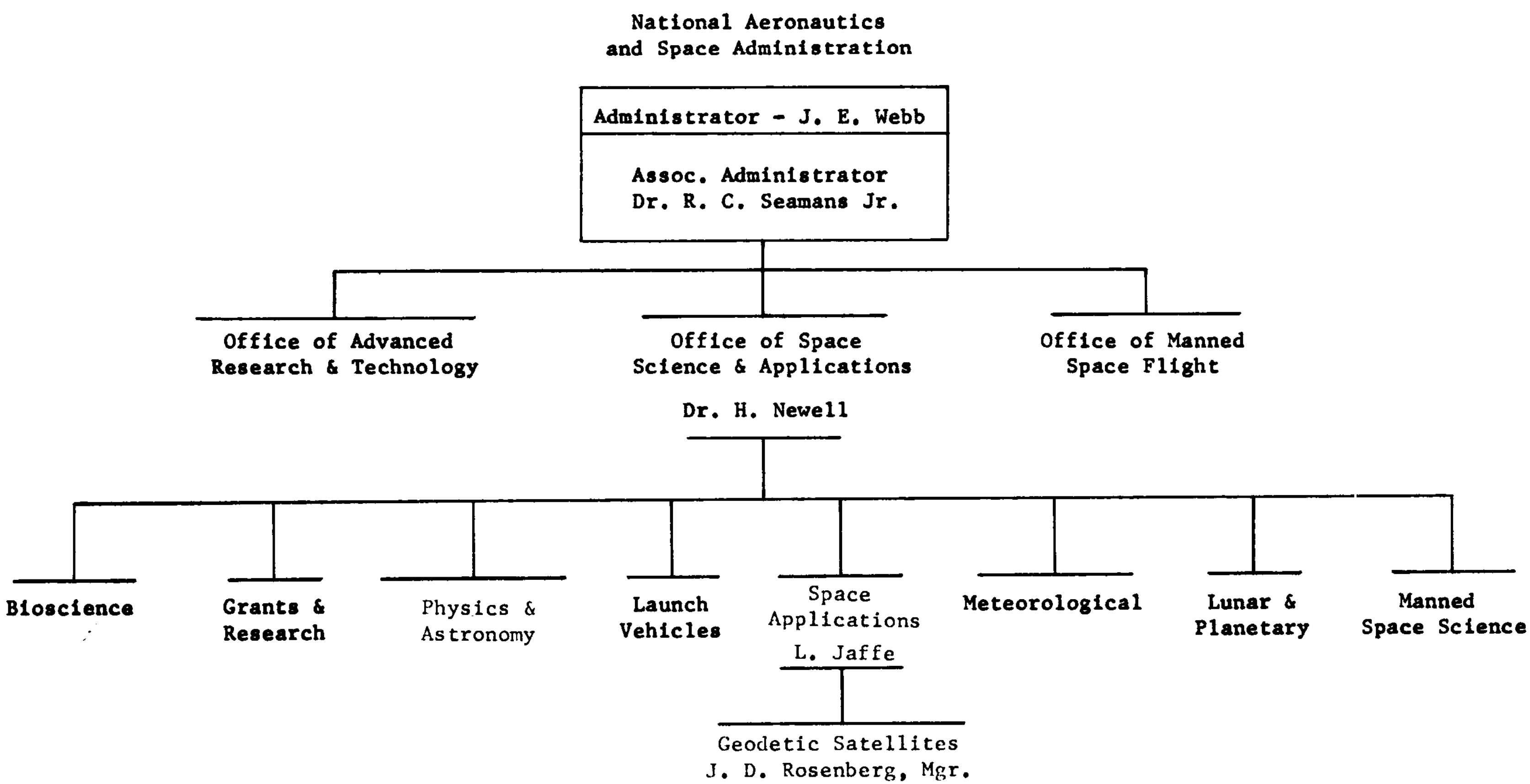


Figure G-1.- NGSP organization.

Information disseminations. - Various types of information will be disseminated by the GOCC, as required, for the purposes of informing the participants of spacecraft and/or project activity.

Data monitoring. - The GOCC will monitor the geodetic operations and maintain up-to-date records of geodetic activity. Records will be maintained to show (1) what data have been forwarded to the Geodetic Satellites Data Service and by whom, (2) who has requested and received data, and (3) participating station locations.

Communications. - Both telephone and teletype communication (ref. 1) will be provided by the Control Center on a 24-hour-per-day 7-day-per-week basis.

All participants will have contact with the GOCC during the course of the program. Although participants may be concerned with data acquisition with only one of the satellites (such as PAGEOS), they may be qualified to receive any of the data forwarded to the Data Center.

Orbital and Ephemeris Information

The Data System Division (DSD) at GSFC will predict satellite orbit data and satellite lifetime and will predict the mutual visibility opportunities for the geodetic network stations. In particular, PAGEOS will impose the following requirements on the DSD:

(1) Establish (if possible) the initial orbital parameters of the Agena vehicle via Minitrack, radar, and optical tracking.

(2) Determine (if possible) conditions at canister separation and balloon deployment via radar and optical tracking.

(3) Establish initial orbital parameters of PAGEOS by means of Agena vehicle and optical tracking and generate 5-year evaluation.

(4) Provide, as required, PAGEOS ephemeris to all qualified experimenters on a regular basis.

The optical tracking data will be obtained from SAO and MOTS on a regular basis. Mutual observation predictions, if requested, should also be available for the Echo I and Echo II satellites.

C&GS Observation Calendar

The C&GS will publish an observation calendar indicating when each of the camera stations will be occupied. This information, if requested, will be distributed through the GOCC to assist local stations attempting to integrate with the primary PAGEOS network.

AMS Logistics Study

The AMS is responsible for conducting a logistics study to determine the most effective deployment of the 12 BC-4 cameras to be used during the PAGEOS program. Orbital ephemeris data, as required, will be supplied by GSFC.

H. DATA STORAGE AND RETRIEVAL

Geodetic Satellites Data Service

The Geodetic Satellites Data Service (GSDS) (refs. 1 and 27), a group within the Space Science Data Center (SSDC) established specifically to handle the National Geodetic Satellites Program observational data, will conduct data exchange activities among the principal investigators associated with GEOS and PAGEOS programs. The principal data exchange activities are the receipt, logging, storage, control, and distribution of observational data prepared by the observing networks.

It is expected that each U.S. and international observer will submit their data reports on a timely basis. The GSDS will perform required liaison with the observers to correct obvious data errors and to inform observers of infractions of reporting format. The GSDS will also perform required liaison with the principal investigators and, upon request, provide processed data (no raw data) from the GSDS storage system.

Data receipt and storage.- All data are to be submitted to the GSDS in the standard format for optical observation (appendix V) with an accompanying inventory sheet. Data will be transmitted to the following address:

NASA Space Science Data Center, Code 257
Attn.: Geodetic Satellites Data Service
Goddard Space Flight Center
Greenbelt, Maryland 20771

Upon receipt of the magnetic tapes (or cards), the data will be visually inspected for damage and obvious mishandling and will then be submitted to a computer program for quality control (QC) checking. The data comprising each station observation will follow one of the following three routes:

(1) Data appear to be acceptable. Observation accepted.

(2) Data questionable. Observation tentatively accepted subject to results of manual analysis.

(3) Data unquestionably incorrect. Observation referred to submitting network for corrective action.

The quality control operation of GSDS consists of two phases (fig. H-1). The first phase documents the characteristics of the observing sites. Each observation site or network participating in the program provides to GSDS a full description of the station locations and the methods used to establish this position. In addition, each observing site is identified by GSDS as to the type of satellite measurement being utilized, error models and theoretical analysis used in data processing, and operational observation

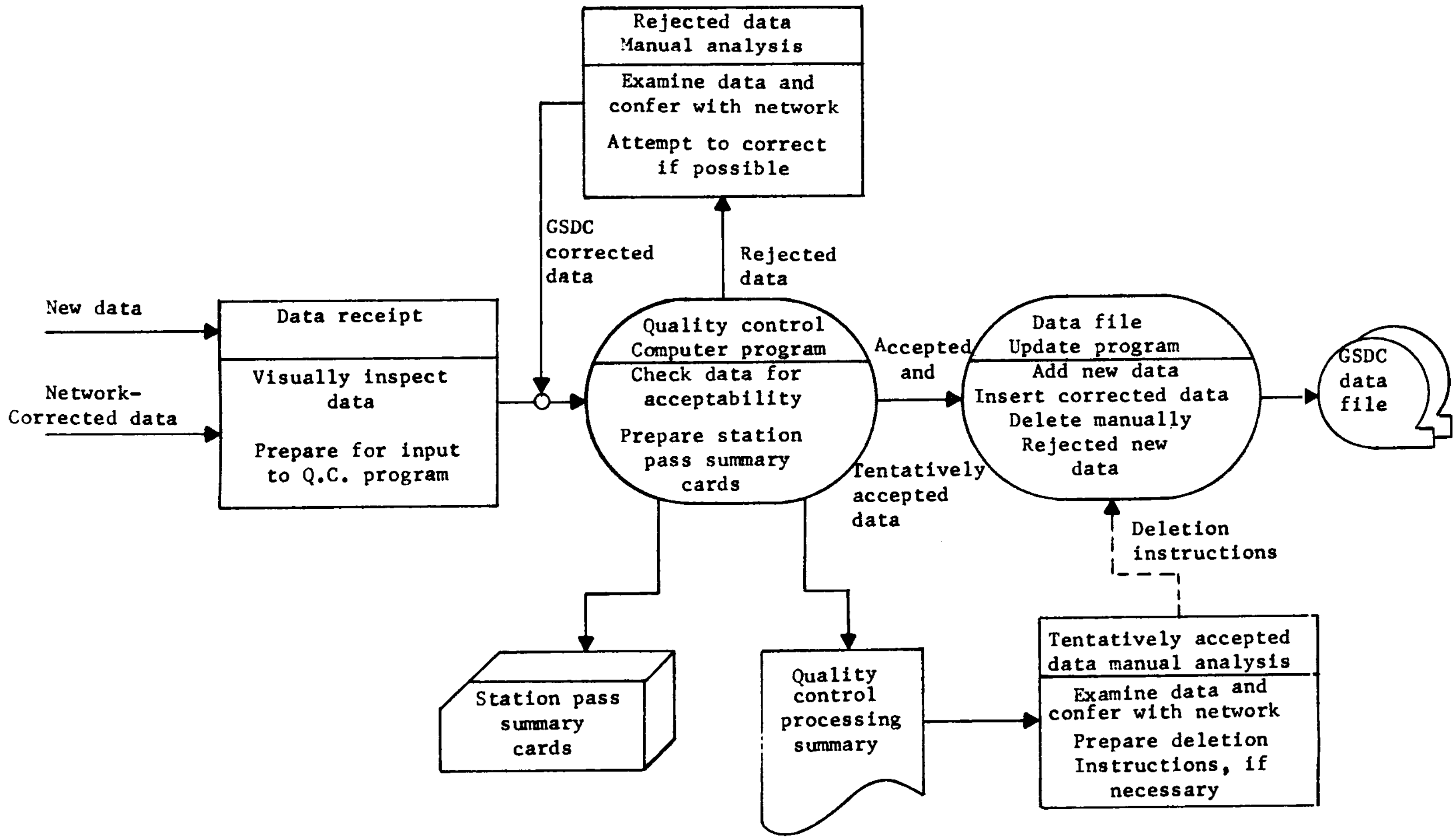


Figure H-1.- GSDS data receipt operation.

procedures. This information is reviewed to determine that the sites are known with sufficient accuracy, and that the observation and reduction techniques and procedures will permit the respective geodetic observations to be of sufficient precision to have geodetic significance.

The second phase of the QC process is intended to eliminate gross errors immediately and minimize the consequences of other errors. Simultaneous observation data will undergo a limited comparison with geometric computations to verify measurement accuracy. Data emanating from stations of unknown positions will also be geometrically tested to verify the coherence of the results. In both geometric test programs, preestablished tolerance limits will be used in control of data quality.

The accepted observations are then merged into the PAGEOS data files where summary cards are prepared for the acceptable data. These cards are used to prepare the Data Catalogs to allow the investigators to select data of interest for analysis.

Data request and retrieval.- The incoming data will be announced through a series of periodic reports. These reports are as follows:

(1) Data Receipt Summary – totals by station of the amount and span of data received, both according to date and during the current reporting period.

(2) Stations Not Reporting List – a list of stations expected to report, but from which GSDS has not received data for a certain time period (for example, the preceding 3 months).

(3) Data Distribution Summary – totals by reporting network of data sent to each investigator to date.

(4) Participating Stations List – a list of station names, positions, datums, participating dates, etc., with special note of changes occurring during the reporting period.

(5) Corrected Data List – a list by network of corrected data that GSDS has received during the current reporting period, including the nature of the correction. This errata list will allow the investigators to keep their catalogs up to date.

The documentation reports generated by the GSDS will be sent to the principal investigators. Additional reports may also be obtained by direct request to the GSDS.

Selected final data will be requested from the GSDS by all principal investigators. When the data distribution request is received at the GSDS, the request is verified with the authorized program participation list. Other individuals or organizations who wish to obtain data may apply to NASA Headquarters. (See sec. G.) If the request is approved, the GSDS data retrieval program is employed (fig. H-2) and the data mailed to the investigator.

Large volume requests for data will be copied on magnetic tape, whereas small orders of data may be distributed on cards, if desired. It is not intended that the retrieval procedure be used to search for data; the catalogs are designed for this purpose. The investigator should request only specific observations or time intervals which closely delimit the data of interest.

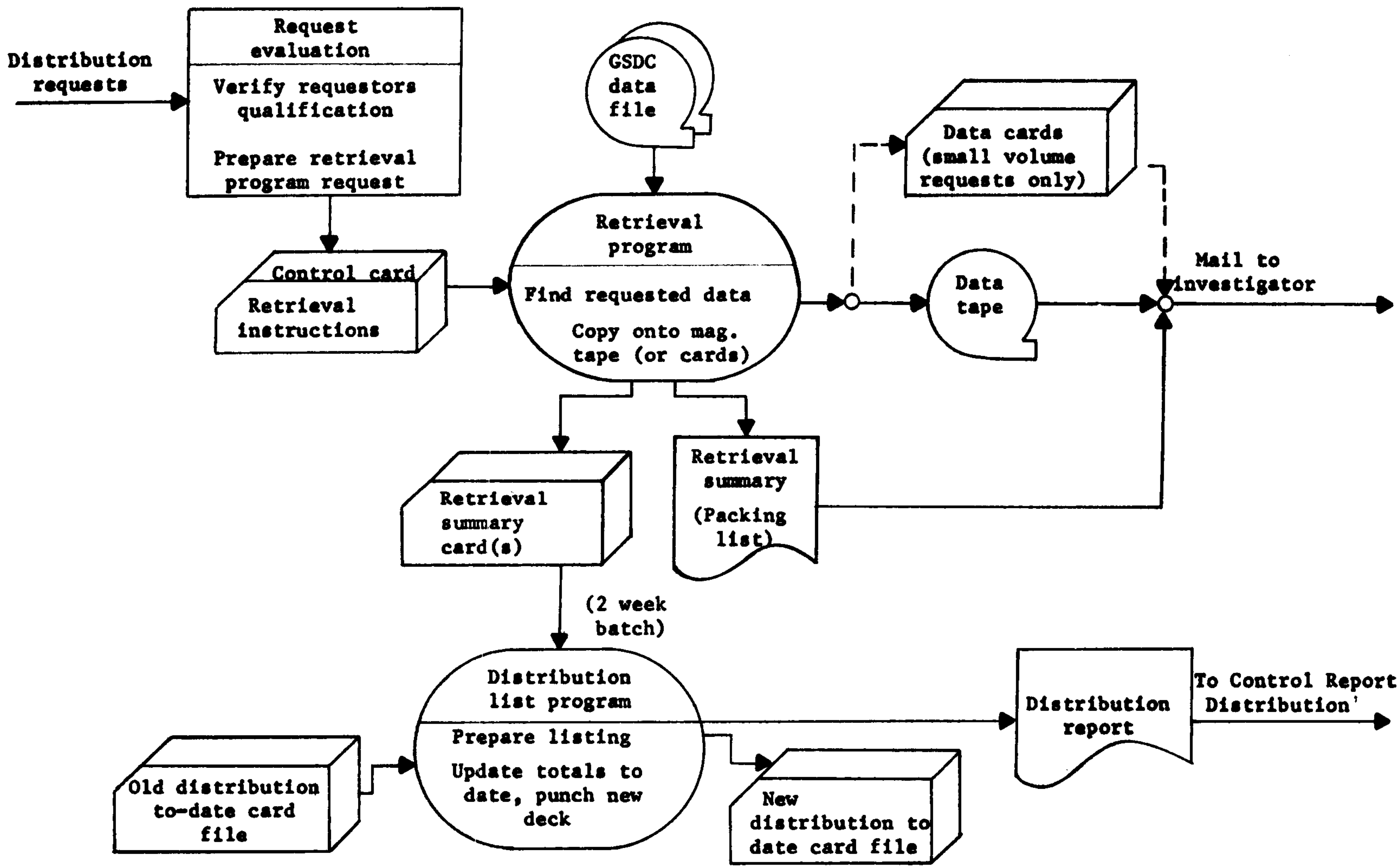


Figure H-2.- GSDS data distribution operation.

J. PAGEOS PROGRAM EXPERIMENTERS

PAGEOS Principal Investigators

Four of the principal investigators in the NGSP will be responsible for the collection and/or analysis of data for the PAGEOS program (see ref. 2): Lawrence W. Swanson, C&GS; John A. McCall, OCE; Charles A. Lundquist, SAO; and Ivan I. Mueller, OSU. A brief description of the data reduction and analysis plans of each investigator is given. Additional information on the plate reduction procedures can be found in reference 28. NASA will publish a document concerning the analysis of the reduced data at a later date.

C&GS and AMS.- The C&GS and Department of Army (under the direction of Lawrence W. Swanson, C&GS, and John A. McCall, OCE) have the responsibility for establishing the primary PAGEOS network. For the PAGEOS project, the C&GS will provide eight BC-4 camera teams and the Army will provide four BC-4 camera teams to obtain and analyze observations at approximately 40 stations throughout the world (see appendix VI) for use in establishing a precise world geometric network independent of the gravitational field. Approximately 3 to 5 years will be required to collect the photographic data (ref. 29) and complete the analysis. The expected accuracy of the coordinates is 8 to 10 meters in latitude and longitude and 16 to 30 meters in height.

The reduction of the camera data, which is an integral part of the C&GS satellite triangulation system, consists of the comparator measurements and a number of computer programs (ref. 3). The work is divided into three principal phases (fig. J-1): (1) preliminary evaluation and computations, (2) plate measurement and accuracy evaluation, and (3) geometric reduction of data. A brief description of the individual tasks shown in figure J-1 follows:

(A) Search the star catalog for the right ascension and declination of the six or seven stars previously identified with the aid of star charts and prepare punched card output of data needed for updating the catalog positions of these stars to the time of observation.

(B) Apply the star catalog data to update the catalog values of right ascension and declination and apply corrections for atmospheric refraction considering the specific zenith distances, diurnal aberration, temperature, and atmospheric pressure at the camera station.

(C) Determine a coherent set of plate coordinates for five images each of approximately 100 stars before satellite passage and 100 stars after satellite passage, approximately 600 satellite images near the center of the satellite trail, and three sets of eight drilled holes measured every 2 hours during the plate-measuring process. The plate is then rotated approximately 180° from the first position and the procedure is repeated.

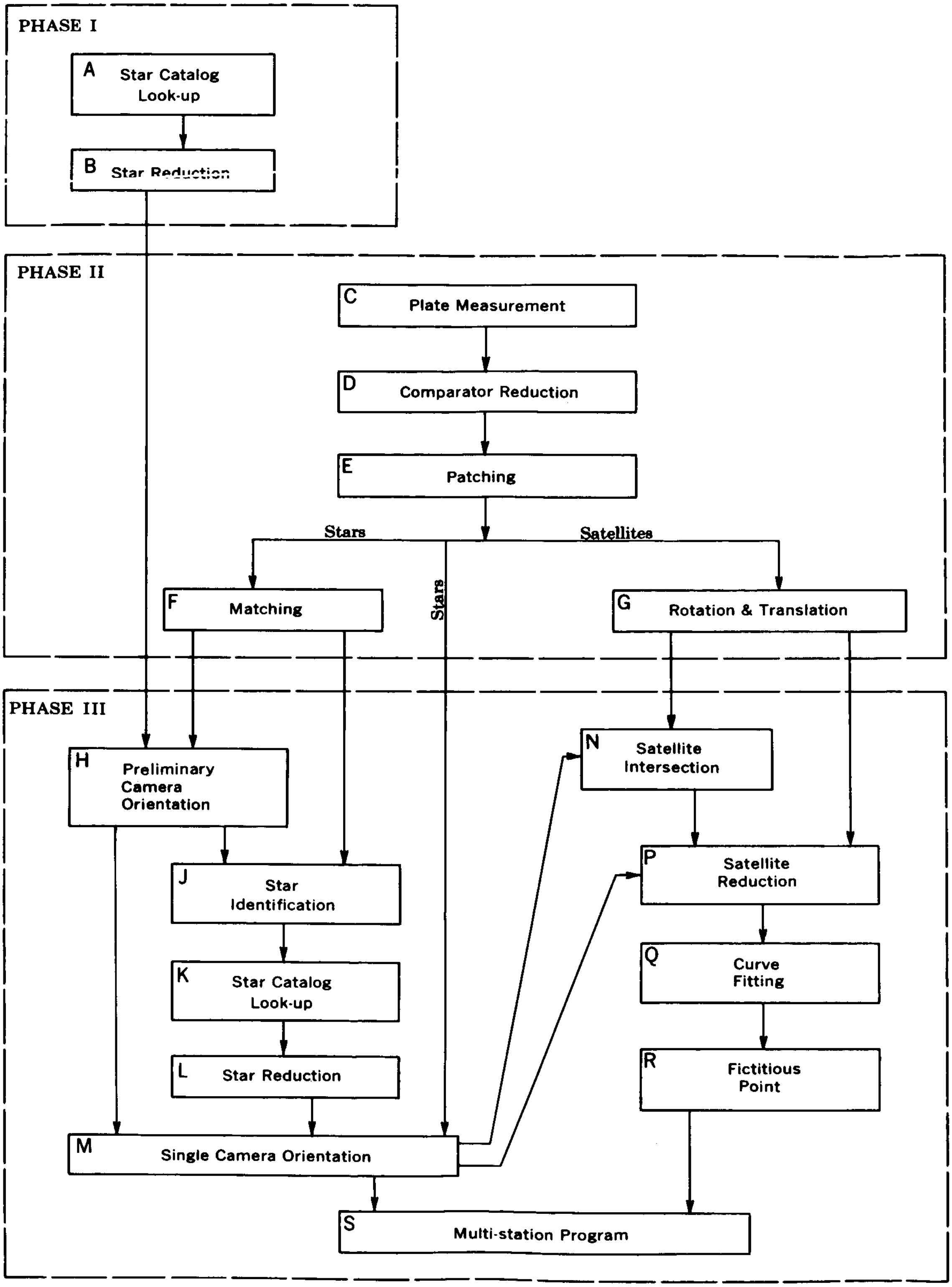


Figure J-1.- Data reduction flow chart.

(D) Transform the raw comparator coordinates of all points to a coordinate system having its origin near the plate center and one of its coordinate axes passing through two of the four corner drilled holes.

(E) Transform each 2-hour set of measurements of the eight drilled holes into a single coherent set.

(F) Combine the refined coordinates of the zero and 180° rotated sets of star image measurements into a single bias-free set by making a "best fit" and further refine the image coordinate values by computing the mean coordinate for each image after the best fit transformation.

(G) Treat the 0° and 180° rotated positions of the satellite images with the same transformations given the star images in task F.

(H) Determine a close approximation of the camera orientation parameters referenced to a local coordinate system.

(I) Omitted in program.

(J) Determine the approximate right ascension and declination of all stars measured on the plate.

(K) Task A is applied again in the identification of all stars.

(L) Task B is applied again to update the catalog data for all stars and make corrections for zenith angle.

(M) Determine the final orientation of the camera using all measured star image coordinates and their updated, refraction corrected, star catalog values.

(N) Convert the approximately known geodetic ellipsoidal coordinates of camera stations to Cartesian coordinates in a chosen reference system. By using the single camera orientation for two or three cameras simultaneously observing the same event and the approximately 600 associated satellite image coordinates, obtain a preliminary position and slant range for each satellite image.

(P) Slant range and satellite positions are used to correct each satellite plate image position for lens distortion, diurnal aberration, atmospheric refraction, phase angle, and differences in light travel time from the satellite to different camera stations.

(Q) Successively fit curves of fifth- through seventh-order polynomials to the image coordinates by using a power series with respect to time to smooth random errors of the satellite imagery.

(R) Generate a fictitious point for the satellite on each plate of an event.

(S) Treat as many camera stations and events as are geometrically coupled with a least-squares adjustment in accordance with any assigned relative weighting among the input data.

SAO.- SAO (under the direction of Dr. Charles A. Lundquist) will utilize the Baker-Nunn cameras in the PAGEOS observational program. (See appendix II for station locations.) In addition to the internally generated data, SAO will be responsible for the analysis and integration of other observational data obtained by the C&GS and international observers for the purposes of determining (1) the position for the Baker-Nunn stations in a common coordinate system and (2) the relationship of the geodetic datums involved, from knowledge acquired of station positions derived from satellite analysis.

A new geometrical geodesy computer program will be prepared to analyze simultaneous observations from two or more stations. This program will refine station positions by geometrical procedures only and will accept data of all types in appropriate simultaneous combinations.

The geometric data will also be integrated with the gravimetric data in an overall adjustment of satellite geodetic results and surface data.

OSU.- Ivan I. Mueller, OSU, is responsible for the analysis of PAGEOS and other satellite data to define a unified world geodetic system for the NGSP. A three-step program will be used in the analysis:

(1) By using simultaneous observations, a determination of the relative positions of observation stations in the Cartesian coordinate system of arbitrary position and orientation will be performed.

(2) By using the orbital method and the preceding results and possibly other observation results, the necessary rotation and shift of the coordinate system used previously will be determined to obtain geocentric coordinates for the stations.

(3) By using the conventional geodetic coordinates of the stations, where available, and their geocentric geodetic coordinates previously determined, the necessary changes in the various national geodetic data parameters will be determined to accomplish the given objectives.

At each step, the data from several geodetic observational systems are analyzed independently and, with a proper weighting procedure, in some combinations with each other.

International Participation

Appendix II contains a list of West European stations which will eventually be able to observe PAGEOS. Stations which are currently operational are Edinburgh, Braunschweig, Delft, Uppsala, and Malvern. In general, a coordinated observation program for the international stations will not be functional until about six months after the launch of PAGEOS. SAO is responsible for the analysis of the international data.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 10, 1966,
855-00-00-00-23.

APPENDIX I

DESCRIPTION OF NGSP OPERATIONAL CAMERAS

The following list describes the cameras that are currently engaged in the GEOS A flashing light program. Many of these cameras are equipped with chopping shutters and will be used during the PAGEOS program to establish additional stations within the primary network.

CAMERA CONSTANTS

Arbitrary camera number	Type	Focal length, mm	Lens aperture, mm	Lens transmission	Image size, μ
1	BAKER-NUNN	500	500	0.97	30
2	MOTS 40 IN	1016	203	0.80	40
3	PTH – 100	1016	203	0.85	40
4	BC-4	304	117	0.70	30
5	BC-4-A	450	117	0.70	30
6	K-40	1200	200	0.70	30
7	SCHMIDT A	600	600	0.60	30
8	SCHMIDT C	1593	400	0.60	15
9	SCHMIDT B	1000	400	0.90	40
10	PHOTOM	8160	510	0.90	8
11	MOTS F 24 IN	610	102	0.70	40
12	PC-1000 AF	1000	200	0.85	30
13	BC-4 CGS	304	117	0.70	35
14	ASKANIA	500	400	0.90	40
15	SCHMIDT D	600	300	1.00	40
16	SCHMIDT F	1031	380	0.70	30
17	SCHMIDT G	678	380	0.80	30
18	MOTS F 40	1016	203	0.80	40
19	GEODETIC 36	914	228.6	0.70	30

APPENDIX I

Arbitrary camera number	Type	Focal length, mm	Lens aperture, mm	Lens transmission	Image size, μ
20	MOD-AIR SUR	300	117	0.70	30
21	SCHMIDT H	1040	400	0.70	30
22	K-37 AER	305	122	0.80	40
23	BOUWERS-MAX	1200	300	0.65	25
24	CASS-REFL	1000	170	0.90	30
25	SCHMIDT I	751	224	0.90	30
26	ZEISS-FK	1200	170	0.80	30

APPENDIX II

SAO, NASA-MOTS, AND WEST EUROPEAN STATIONS

The SAO and West European stations will be integrated with the C&GS primary network into a worldwide geometric network by SAO. The NASA-MOTS stations depend upon the addition of chopping shutters to the MOTS 40-inch cameras before they can participate in the program. Additional stations may be included in the program as it progresses; this information will be available from the GOCC.

SAO Stations

Station number	Station	Latitude	Longitude
1	Oregon Pass, New Mexico, U.S.A.	$32^{\circ}25'$ N	$253^{\circ}27'$ E
2	Olifantsfontein, South Africa	$25^{\circ}58'$ S	$28^{\circ}15'$ E
3	San Fernando, Spain	$36^{\circ}28'$ N	$353^{\circ}48'$ E
4	Tokyo, Japan	$35^{\circ}40'$ N	$139^{\circ}32'$ E
5	Naini Tal, India	$29^{\circ}22'$ N	$79^{\circ}27'$ E
6	Arequipa, Peru	$16^{\circ}28'$ S	$288^{\circ}30'$ E
7	Shiraz, Iran	$29^{\circ}38'$ N	$52^{\circ}31'$ E
8	Curacao, Netherlands West Indies	$12^{\circ}05'$ N	$291^{\circ}10'$ E
9	Jupiter, Florida, U.S.A.	$27^{\circ}01'$ N	$279^{\circ}53'$ E
10	Villa Dolores, Argentina	$31^{\circ}57'$ S	$294^{\circ}54'$ E
11	Naui, Hawaii, U.S.A.	$20^{\circ}43'$ N	$203^{\circ}44'$ E
12	Island Lagoon, Australia	$31^{\circ}24'$ S	$136^{\circ}53'$ E
*13	Cold Lake, Alberta, Canada	$54^{\circ}45'$ N	$249^{\circ}57'$ E
*14	Edwards AFB, California, U.S.A.	$34^{\circ}58'$ N	$242^{\circ}05'$ E
*15	Oslo, Norway	$60^{\circ}13'$ N	$10^{\circ}45'$ E
*16	Johnston Island	$16^{\circ}45'$ N	$190^{\circ}29'$ E
†17	Jupiter, Florida, U.S.A.	$27^{\circ}01'$ N	$279^{\circ}53'$ E
†18	Harvard, Massachusetts, U.S.A.	$42^{\circ}30'$ N	$288^{\circ}26'$ E

*USAF stations to be integrated into Baker-Nunn network by SAO.
†These stations are equipped with SAO's Geodetic-36 camera.

APPENDIX II

NASA-MOTS Stations

Station number	Station	Latitude	Longitude
1	Blossom Point, Maryland, U.S.A.	38°26' N	282°55' E
2	College, Alaska, U.S.A.	64°52' N	212°10' E
3	Fort Myers, Florida, U.S.A.	26°33' N	278°08' E
4	Mojave, California, U.S.A.	35°20' N	243°06' E
5	Quito, Ecuador	00°37' S	281°25' E
6	Lima, Peru	11°47' S	282°51' E
7	Santiago, Chile	33°09' S	289°20' E
8	Winkfield, England	51°27' N	359°18' E
9	Johannesburg, South Africa	25°53' S	27°42' E
10	St. Johns, Newfoundland	47°44' N	307°17' E
11	Woomera, Australia	31°29' S	136°52' E
12	Tananarive, Madagascar	19°01' S	47°18' E

West European Stations

Station number	Station	Latitude	Longitude
1	Early Point Edinburgh	55°44' N	356°46' E
2	Tuorla Observatory	60°25' N	22°27' E
3	Munchen-Hohenpeissenberg	47°48' N	11°01' E
4	Munchen	48°09' N	11°34' E
5	Bochum	51°26' N	07°12' E
6	Berlin	52°29' N	13°26' E
7	Braunschweig-Wesendorf	52°35' N	10°30' E
8	Frankfurt	50°05' N	08°31' E
9	Delft	52°00' N	04°22' E
10	Uppsala	59°52' N	17°36' E
11	Lovo	59°20' N	17°48' E
12	Zimmerwald	46°53' N	07°28' E

APPENDIX II

Station number	Station	Latitude	Longitude
13	Malvern	52°09' N	358°01' E
14	Meudon	48°48' N	02°14' E
15	Hautes-Alpes	43°56' N	05°23' E

APPENDIX III

PAGEOS ORBITAL PREDICTIONS AND PRELIMINARY OPTICAL ANALYSIS

Predictions of the orbital behavior of PAGEOS and preliminary analysis of its optical properties indicate that the satellite has been successfully launched into a 5-year lifetime orbit and has optical properties commensurate with the requirements for conducting worldwide satellite triangulation measurements.

PAGEOS Orbit

A 5-year analysis of the PAGEOS orbit has been performed using a modified "Lifetime 18" computer program. The maximum predicted variation of several parameters is given:

	Initial	Maximum 5-year variation
Semimajor axis, km	10614.79	10551.26
Eccentricity	0.000248	0.205792
Inclination, deg	86.9739	83.7605
Apogee, km	4262.94	6344.48
Perigee, km	4210.30	2001.73

A 5-year plot of the predicted altitude variations of PAGEOS is given in figure III-1.

PAGEOS Optical Properties

Photographs taken of PAGEOS during the first 2 weeks after launch indicate no apparent brightness variations in the image. A 24-inch telescope located on Mt. Palomar, equipped with a photoelectric readout, has obtained data on 10 passes of PAGEOS through July 9, 1966. Preliminary analysis of the data indicates that the satellite surface is 96.79 percent specular and the mean radius of curvature is 49.39 feet.

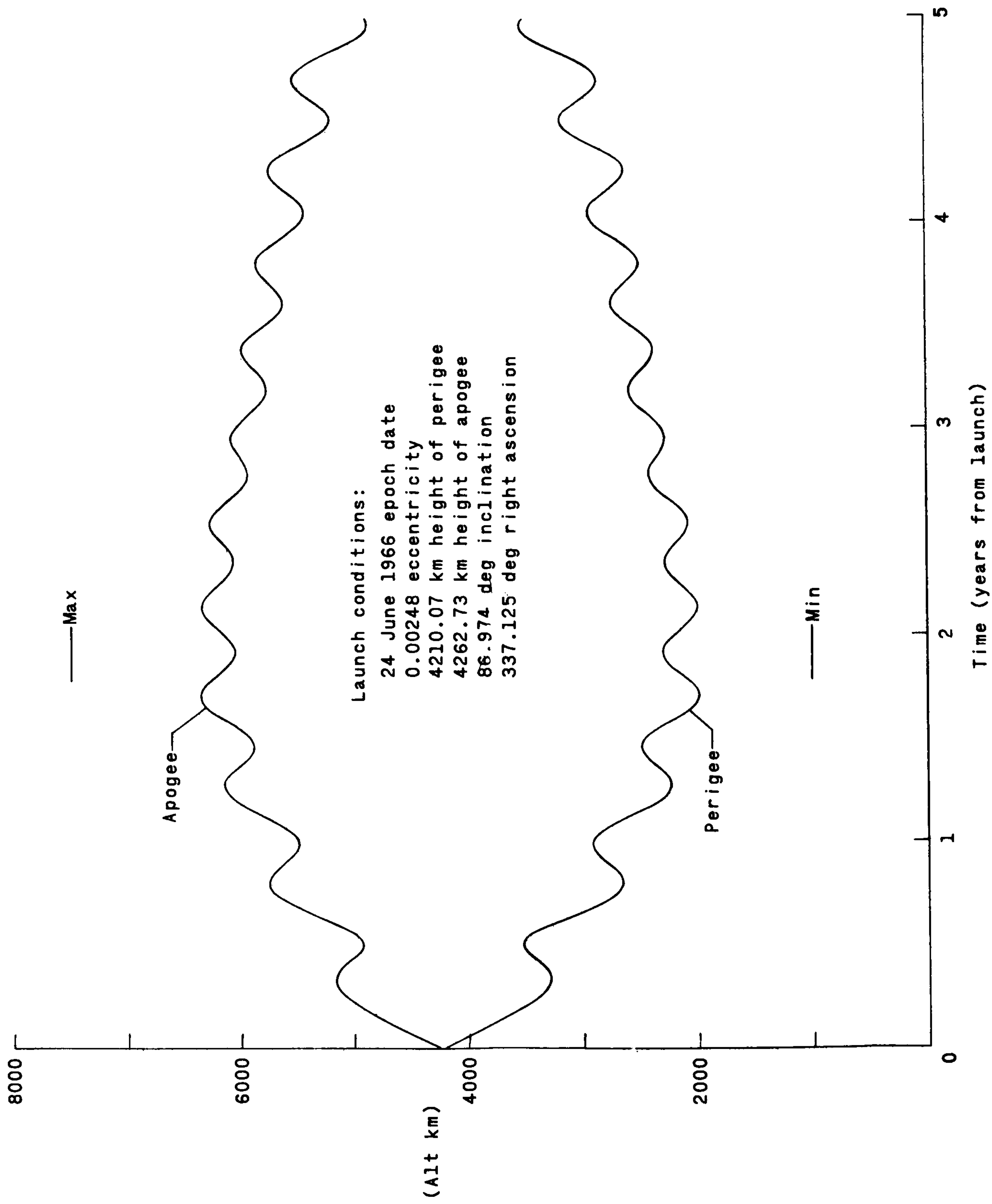


Figure III-1.- Predicted PAGEOS altitude as a function of time after launch.

APPENDIX IV

PREDICTED 2-YEAR OBSERVATION CALENDAR FOR BASE LINES IN PROPOSED 36-STATION NETWORK

The total predicted simultaneous viewing opportunities for the 102 base lines in the original 36-station network are given for each 30-day interval during the first 2 years after launch. An estimate of the viewing opportunities during the remaining 3 years can be obtained by comparing the 2-year totals with the 5-year totals given in figure D-10.

APPENDIX IV

YEARS AFTER LAUNCH (30-DAY INTERVALS)

0 1 2

Base line																									
1-2					27	40	43	30	33	8							3	32	5						
1-3					33	37	40	37	37	10								21	21	3	11				
1-4					8	31	16	6	6								10	20	8						
1-5						8	35	15										3	20	3					
1-6					12	49	68	44	12								12	43	51	10					
1-7					6	15	29	22	17								6	24	5						
2-3			15	26	28	7	18	13	14	16				13	1			11						2	4
2-7		1	15	16	14	3	8	4	6	10				7	4			5							6
2-8		19	27	17	27	8	9			14	1		7	20	29	1					7				6
2-9		9	23	2	28	8	13			17	9		2	21	28	17		4			14				4
2-10		1	21	19	23	3	7			15	5			15	19	8		1							4
3-4			7	15	6		4	15	8									11							
3-10		3	29	30	22	18	16			21	3			21	29	1	2	3			11			2	10
3-11		2	16	21	19	6	9			15	4			7	17	1		7							5
4-5				3	7	12	26	32	17								19	30	22	6					
4-11		7	30	26	21	6	12		2	8					7	3		6			9			1	
4-12		3	26	32	7	23	24			29	3				10			10			2	10			
4-13			10	19	28	9	10		4	12	3										6				
5-6				14	34	58	87	54	29	1							9	55	73	21					
5-13				17	19	17	19	2	12	8							6	16			3				
5-14				16	34	24	28		4	22								17			10				
5-15				9	39	17	21	9	23	17	2							10	2		5				
6-7				6	35	14	9	14	12	12								7							
6-15				11	30	16	28	12	27	6							4	29	2						
6-16				7	50	28	38	7	17	21	6						7	29			11				
7-8		5	19	21	21	3	10			9	7			12	20	7					6	2			9
7-16		1	15	16	29	1	11	1	2	11				12	8			5							10
7-17		21	26	18		5	13			16	1		11	21	20			1			8			5	10
8-9	1	12	13	1	30	1	7	11		22			9	11	17	23			2		23		1		
8-17		11	2		9		3			8				1	5	4					5				
8-18	2	16			18	1	1	13	5	3			4			15			1	5	20	3			
8-19	4	11			23		5	26	3	12		2	4			19	3			5	21		5		
9-10	1	9	8		17		4	8		15			10	8	9	11				1	5			3	1
9-19	13	12		1	27	9			19	17		5	10			21	1		9	15	25		11		
9-20	2	15		6	15		4	20	15				2			8	1		10	13	8				
10-11		5	10	3	10		2			7				6	11	3									
10-20	8	15			23	4	4	16		2		5	6			18	7	5		1	20		7		
10-21		11	2		13		7	10		6	5		2		5	13			1		10				
11-12		8	16	10	18		7			12	2			10	18									4	7
11-21	7	25	4	5	10	8	7	3		15	1	3	10		4	15	1	3			9	2			
11-22		14	2		15	1	10	5		19	10				8	17					14				
12-13		10	17	10	12	2	11			13	2		4	5	20						9			7	8
12-22	8	24	2		16	7	5	4		14		1	12		7	12	1	2			7	12			
12-23		14	6		13		10	6		15	5		3	3	11	17		3			13				
13-14		3	13	13	26	3	9	4	11			1	8	11							4			6	10
13-23	4	20	9		25	9	8	3		12	8		9	4	11	21	1				14	5			
13-24		6	11		19	2	8			12	6		1	7	17	17					3				
14-15		6	23	19	29	8	14			16			5	14	14			4			3			4	14
14-24	8	23	17		6	3	9	2		17	5	1	18	16	24	6		5			16	4	6	3	
14-25	2	19	29	18	12	2	11	4		14	12		7	19	26	8		6			2	5		8	8
15-16		1	17	20	33	6	13	4	7	13				13	7			7							5
15-25	1	21	27	17		4	13			16	2		13	23	21						13			3	9
15-26		7	22	19	24	2	11			9	10			18	20	6		2							6

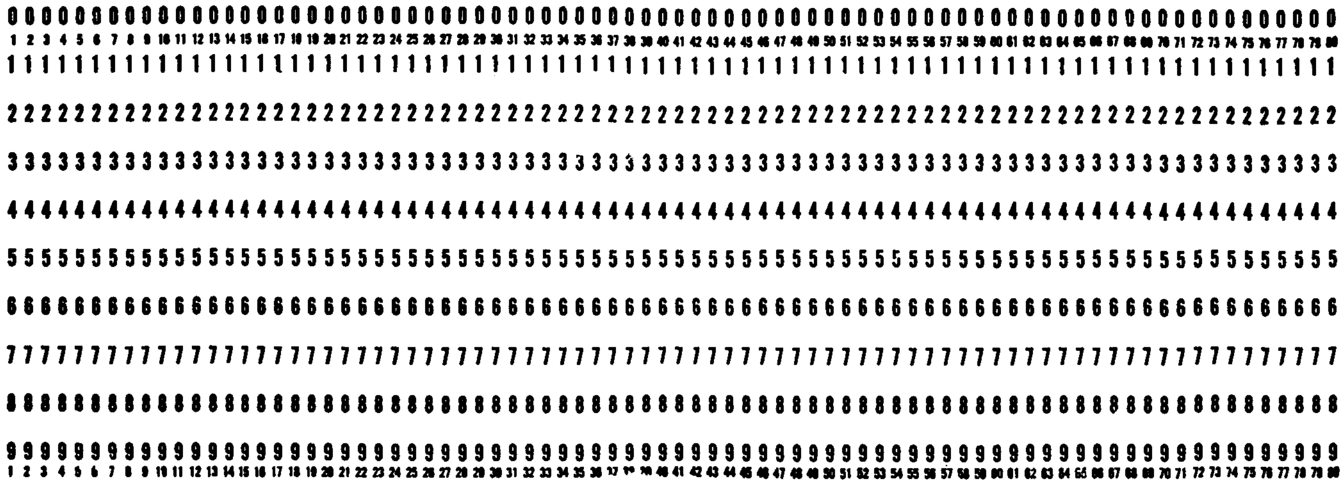
0 1 2

Base line																									
16-17		8	23	18	5	2	10	1		10	9		2	19	19			5			9	4			6
16-26	4	26	28	18	1	3	14			25	3	2	18	25	19						11		8	7	7
17-18	2	16			19		11	21		4		1	6			17		8	1	4	17		7		
17-26		10	7		13		3	1		11	2		3	4	8	5					9				
17-27	5	13			23	1		10		20	9		2			13				6	19	6			
18-19	6	19		14	10		2	15	14				4		5	6			8	16	5		2	3	
18-27		12		9	4			6	4	13	2					6				10	3				
18-28	22	21	2	29	7				6			11	6		7	18							18	3	
19-20	3	24	3	13	5			9	13				2						4	14	2				
19-28	11	35	26	27	14				1			3	3		8	7							1	4	
19-29	25	41	29	17								13	4		7								25	1	
20-21	2	12		11	12			15	13				3			5			5	13	7		2		
20-29	27	29	19	21						16	34	14	1			7									
20-30	7	17	9	19	4			10	13				3		7				3	11			4	2	
21-22	1	14		4	13			12	10							17			5	8	24				
21-30	22	17		19	14		4	24	29			11	7			15	1		22	28	18	5	17		
22-23		12		3	14			9	9	17			1			15			2	3	16				
22-30	6	13		15	22			11	27				3			15			5	21	17		6		
22-31	15	14		16	11			20	29			6	5			8			15	17	13	4	2		
23-24		6	1	2	11			5	6	15			1			15				1	4				
23-31	11	12		7	21			5	27	31	17	3	2			14				13	26				
23-32	4	10		6	8		6	22	23	1			2			7			13	16	7				
24-25	2	17	6		19	1	2	9	1	11			5	4	8	12				4	1	4		1	
24-32	12	12		9	24	3		12	30			8				21	4		9	16	23		10		
24-33	3	11		6	11		3	18	24	27	16					5			2	16	1				
25-26		10	3		12		5	1		9	4		2	4	6	2									
25-33	7	12		2	20		1	16	12	34	25					13	6			4	19	7			
25-34	2	12		2	22		8	18	10	18	3					16		1	3		14		4		
26-27	3	15		1	25		10	25	8	5		3	6			23		6	1	3	22		11		
26-34	8	19		1	24	7	4	17	8	6		4	6			21	6			3	15	7			
27-28	10	21	17	15					2	9	2	4	2		4	2							6	6	
27-34	6	25	5	16	9		2	16	7			1	4			12		3	4	3	13				
27-35	9	25	22	27						18	30	5				3									
28-29	78	68	39	9							30	70	71	52	20						1	30	35	41	15
28-35	65	57	32	15							9	64	49	36	22	7						9	41	38	25
29-30	13	16	21	18						1	9	9	15		11	3									
29-35	42	33	11								2	27	41	24	1									9	10
29-36	42	22	7								6	24	39	27									9	13	
30-31	13	32	25	17	4			3	12			1	13		9			2	1	4			19	4	
30-36	12	29	29	5								3	10									13	15	4	
31-32	6	21	17	20	2				20	2			5		5	1			2	11			4	5	
31-36	45	48	50	26							4	30	40	11	33	1					7	17	46	11	7
32-33	10	24	16	21	5			7	15				3		2			2	9	10					
32-36	29	31	36	39	4							11	17		13	17							4	5	
33-34	10	17	13	22	9			9	9			1	5		3	10			8	4	4		6	3	
33-35	28	29	37	20								21	15		9							10	22	15	
33-36	8	26	38	25	1					25	22	6	5												
34-35	17	21	16	26						10	24	18	4		3								6	5	
35-36	41	23	23	7	38	1			15	28	45	54	50	48	11	57	4				4	2	1	37	34

APPENDIX V

NGSP FORMAT FOR OPTICAL OBSERVATIONS

The following format must be used when submitting preprocessed optical data to the Geodetic Satellites Data Service. One card is sufficient to describe the "fictitious" satellite position generated during the C&GS data reduction procedure.



Field	Columns	Description
1	1 - 6	Satellite identification*
	1 - 2	Year of launch
		64 1964
		65 1965
		66 1966
		etc.
	3 - 5	Order of launch
	6	Component identifier
		1 a
		2 b
		3 c
		4 d
		etc.
2	7	Type of coordinates
		1 Right ascension and declination
		2 Range
		3 Range rate
		4 Frequency shift
		5 Direction cosines
		6 X,Y angle
		7 Azimuth and elevation angle

*As per COSPAR numbering system.

APPENDIX V

Field	Columns	Description
3	8	Observation identifier
		0 Active (observation on beacon)
		1 Passive (chopping shutter)
		2 Camera in conjunction with laser
		3 Laser angular data
4	9 - 11	Timing standard deviation
	9	Milliseconds
	10 - 11	0.01 millisecond
5	12 - 13	Time identifier
		00 UT-0 determined at observing station
		01 UT-1 determined at observing station
		02 UT-2 determined at observing station
		03 UT-C determined at observing station
		04 A.1 determined at observing station
		05 through 49 Other systems**
		50 UT-0 Satellite time
		51 UT-1 Satellite time
		52 UT-2 Satellite time
		53 UT-C Satellite time
		54 A.1 Satellite time
		55 through 99 Other systems
6	14 - 18	Station number
	14	System designator
		0 COSPAR
		1 AFCRL
		2 SAO
		3 STADAN
		4 TRANET DOPPLER
		5 AMS
		6 C&GS
		7 Naval Observatory
		8 International participants
	15 - 18	Station number

**As described in the associated preprocessing report; number assigned at NSSDC before transmitting data to various investigators.

Field	Columns	Description
7	19 - 34	GMT of observation
	19 - 20	Year of observation 64 1964 65 1965 66 1966 etc.
	21 - 22	Month of observation
	23 - 24	Day of observation
	25 - 26	Hour of observation
	27 - 28	Minute of observation
	29 - 30	Second of observation
	31 - 34	0.0001 second of observation
8	35 - 53	Observation data
	35 - 37	Right ascension (R.A.) (hours)/Azimuth degrees (arc), 0° North/X angle (degrees arc). Sign of X angle appears in column 35
	38 - 39	R.A. minutes (of time)/Azimuth minutes (arc)/X angle 0.01° (arc)
	40 - 41	R.A. seconds (time)/Azimuth seconds (arc)
	42 - 44	R.A. 0.001 second (time)/Azimuth 0.001 second (arc)
	45	Sign of declination/Y angle (+) (-)
	46 - 47	Declination degrees (arc)/Elevation angle degrees (arc)/Y angle degrees (arc)
	48 - 49	Declination minutes (arc)/Elevation angle minutes (arc)/Y angle 0.01° (arc)
	50 - 51	Declination seconds (arc)/Elevation angle seconds (arc)
	52 - 53	Declination 0.01 second (arc)/Elevation angle 0.01 second (arc)
9	54 - 59	Date of plate reduction
	54 - 55	Year of reduction 64 1964 65 1965 66 1966 etc.

Field	Columns	Description
	56 - 57	Month of reduction
	58 - 59	Day of reduction
10	60 - 71	Coded information
	60 - 61	Supplementary documentation
		03 SAO reduction procedure report
		04 MOTS plate reduction procedure report
		05 ACIC plate reduction procedure report
		06 C&GS plate reduction procedure report
		07 NASA Goddard R and R preprocessing report
		09 NASA Goddard laser preprocessing report
		10 AFCRL laser reduction procedure report
		11 International preprocessing reports
		12 AMS plate reduction report
		. (Additional numbers will be assigned by NSSDC as required)
		.
		.
		n
	62 - 63	Equator designation
		01 Mean standard equator
		02 Mean equator at Jan 0.0 of year of observation
		03 Mean equator at instant of observation
		04 Mean equator at arbitrary time (Arbitrary system to be defined in associated preprocessing report)
		11 True standard equator
		12 True equator at Jan 0.0 of year of observation
		13 True equator at instant of observation
		14 True equator at arbitrary time (Arbitrary system to be defined in preprocessing report)

Field	Columns	Description
	64 - 65	Equinox designation
		01 Mean standard equinox
		02 Mean equinox at Jan 0.0 of year of observation
		03 Mean equinox at instant of observation
		04 Mean equinox at arbitrary time (Arbitrary system to be defined in associated preprocessing report)
		11 True standard equinox
		12 True equinox at Jan 0.0 of year of observation
		13 True equinox at instant of observation
		14 True equinox at arbitrary time (Arbitrary system to be defined in associated preprocessing report)
	66 - 67	Instrumentation type
		00 PC-1000 MOD-1
		01 PC-1000 MOD-2
		02 BC-4 450 mm
		03 BC-4 300 mm
		04 BC-4 210 mm
		05 Baker-Nunn SAO
		06 Baker-Nunn - military
		07 MOTS
		08 1200 mm ballistic camera
		09 600 mm ballistic camera
		10 MOTS 24-inch
		11 International types
	68 - 69	Catalog identification
		01 BOSS
		02 SAO combined
		03 FK-4
		04 NASA combined
		05 AKG-2
		06 AMS combined
		07 Cape Zone, volume 1
		08 Yale, volume 1
		09 Others (to be defined in the associated preprocessing reports). Code number to be assigned by NSSDC.

APPENDIX V

Field	Columns	Description
	70 - 71	Catalog epoch 01 1855.0 02 1875.0 03 1900 0 04 1950.0 05 1965.0 06 Others (to be defined in the preprocessing reports). Code numbers to be assigned by NSSDC.
11	<u>72 - 80</u>	<u>Description of random error</u>
	72	Standard deviation in right ascension (R.A.) (seconds of arc) multiplied by the cosine of the declination/standard deviation in Azimuth (seconds of arc)/standard deviation in X angle (degrees of arc)
	73 - 74	Standard deviation R.A. (0.01 second of arc) multiplied by the cosine of the declination/standard deviation in X angle (0.01° of arc)
	75	Standard deviation in declination (seconds of arc)/standard deviation in elevation angle (seconds of arc)/standard deviation in Y angle (degrees of arc)
	76 - 77	Standard deviation in declination (0.01 second of arc)/standard deviation in elevation angle (0.01 second of arc)/standard deviation in Y angle (0.01° of arc)
	78 - 80	Covariance; sign in column 78 (+) (-), decimal assumed between columns 79 and 80

APPENDIX VI

REVISED C&GS GEOMETRIC SATELLITE NETWORK

The original 36-station network proposed by the C&GS has been changed because of the predicted simultaneous observations and logistic support availability. The revised network contains 40 stations. A tentative station occupation calendar is given. This information will be available from the GOCC when the PAGEOS program is operational.

APPENDIX VI

REVISED NETWORK STATIONS AND OCCUPATION CALENDAR

No.	Station	Latitude	Longitude	1966				1967				1968				1969			
				1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
001	Thule, Greenland (Denmark)	$76^{\circ}32'$ N	$58^{\circ}45'$ W			x	x	x											
002	Beltsville, Maryland, USA	$39^{\circ}02'$ N	$76^{\circ}55'$ W			x	x	x	x	x									
003	Moses Lake, Washington, USA	$47^{\circ}06'$ N	$119^{\circ}16'$ W			x	x	x											
004	Shemya, Alaska, USA	$52^{\circ}50'$ N	$173^{\circ}10'$ E			x	x	x											
005																			
006	Tromso, Norway	$69^{\circ}40'$ N	$18^{\circ}55'$ E			x	x	x											
007	Lajes AFB, Teiceira, Azores – (Portugal)	$37^{\circ}45'$ N	$25^{\circ}35'$ W			x	x	x	x	x	x	x							
008	Paramaribo, Surinam	$05^{\circ}46'$ N	$55^{\circ}20'$ W						x	x	x	x							
009																			
010																			
011	Maui, Hawaii, USA	$20^{\circ}54'$ N	$156^{\circ}26'$ W			x	x	x	x	x									
012	Wake Island (USA)	$19^{\circ}16'$ N	$166^{\circ}39'$ E			x	x	x					x	x					
013	Kagoshima, Kyushu, Japan	$31^{\circ}30'$ N	$130^{\circ}42'$ E			x	x	x					x	x					
014	Tinsukia, India	$27^{\circ}29'$ N	$95^{\circ}21'$ E										x	x					
015	Mashad, Iran	$36^{\circ}15'$ N	$59^{\circ}45'$ E			x	x	x			x	x	x	x					
016	Palermo, Sicily, Italy	$38^{\circ}09'$ N	$13^{\circ}20'$ E			x	x	x			x	x							
017																			
018	Trindade Island (Brazil)	$20^{\circ}30'$ S	$29^{\circ}20'$ W								x	x							
019	Villa Dolores, Argentina	$31^{\circ}57'$ S	$65^{\circ}09'$ W						x	x	x	x							
020	Easter Island (Chile)	$27^{\circ}09'$ S	$109^{\circ}25'$ W						x	x									
021																			
022	Pago Pago, American Samoa (USA)	$14^{\circ}16'$ S	$170^{\circ}42'$ W			x	x	x	x	x					x	x	x	x	
023	Cape York, Australia	$12^{\circ}21'$ S	$143^{\circ}18'$ E										x	x					
024																			
025																			
026																			
027	Springbok, South Africa	$29^{\circ}42'$ S	$17^{\circ}55'$ E								x	x	x	x	x	x	x	x	
028	Saunders Island, S. S. I. (U.K.)	$57^{\circ}48'$ S	$26^{\circ}28'$ W								x	x			x	x	x	x	
029																			
030																			
031	Queenstown, New Zealand	$45^{\circ}02'$ S	$168^{\circ}45'$ E												x	x	x	x	
032	Perth, Australia	$31^{\circ}52'$ S	$115^{\circ}50'$ E										x	x	x	x	x	x	
033																			
034																			
035																			
036																			
037	Galapagos Island (Ecuador)	$00^{\circ}59'$ S	$90^{\circ}59'$ W						x	x									
038	Revilla Gigedo Islands (Mexico)	$18^{\circ}50'$ N	$111^{\circ}00'$ W			x	x	x	x	x									
039	Oeno Island (U.K.)	$23^{\circ}50'$ S	$130^{\circ}50'$ E						x	x									
040	Cocos (or Keeling) Island (Australia)	$12^{\circ}00'$ S	$96^{\circ}45'$ E										x	x					
041	Mangalore, India	$12^{\circ}55'$ N	$75^{\circ}00'$ E										x	x					
042	Addis Ababa, Ethiopia	$9^{\circ}00'$ N	$38^{\circ}44'$ E								x	x	x	x					
043	Punta Arenas, Chile	$52^{\circ}10'$ S	$70^{\circ}54'$ W						x	x	x	x			x	x	x	x	
044	Heard Island (Australia)	$53^{\circ}08'$ S	$73^{\circ}42'$ E										x	x	x	x	x	x	
045	Mauritius, Mascarene Island (U.K.)	$20^{\circ}25'$ S	$57^{\circ}40'$ E										x	x					
046																			
047	Zamboanga, Philippines	$06^{\circ}56'$ N	$122^{\circ}04'$ E										x	x					
048	Caroline Island (U.K.)	$09^{\circ}58'$ S	$150^{\circ}13'$ W						x	x									
049	Bata, Rio Muni (Spain)	$01^{\circ}50'$ N	$09^{\circ}47'$ E								x	x							
050	Palmer Station, Antarctica (U.S.)	$64^{\circ}40'$ S	$64^{\circ}23'$ W												x	x	x	x	
051	Mawson Station, Antarctica (Australia)	$67^{\circ}36'$ S	$63^{\circ}00'$ E												x	x	x	x	
052	Wilkes Station, Antarctica (Australia)	$66^{\circ}15'$ S	$110^{\circ}38'$ E												x	x	x	x	
053	McMurdo Station, Antarctica (U.S.)	$77^{\circ}50'$ S	$166^{\circ}40'$ E												x	x	x	x	
054	Amundsen-Scott Station, Antarctica (U.S.)	$90^{\circ}00'$ S	$00^{\circ}00'$												x	x	x	x	
055																			
056	Sal Island, Cape Verde Islands	$16^{\circ}40'$ N	$22^{\circ}54'$ W								x	x							

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